The root environment as influenced by mulches, on two different soil types and the resulting effect on fruit yield and sunburn of ‘Cripps’ Pink’ apples.

BY
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DECLARATION

I, the undersigned, hereby declare that the entirety of the work contained in this thesis is my own original work and that I have not previously, in its entirety or in part, submitted it at any university for obtaining any qualification.

Signature Date

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SUMMARY

An investigation into the effects of different mulches on the root environment, encompassing physical, chemical and biological factors of the soil, on two different soil types was done in the form of a field trial on 'Cripps' Pink' apples. Three organic mulches were tested: compost, vermi-castings and woodchips, as well as an inorganic mulch, geotextile fabric, and were compared against clean cultivation.

The organic treatments resulted in improved physical conditions (lower bulk densities) in the heavier soil, as well as, a reduction in temperature fluctuations and a general increase in soil temperatures during the seasons, in both sites. The geotextile fabric treatment resulted in increased soil moisture levels in the top 40 cm, predominantly in the heavier soil. The compost treatment resulted in high soil moisture levels in the top 40 cm only in the lighter soil.

The vermi-castings treatment achieved superior results in terms of changing the nutrient status of the heavier soil. It resulted in significantly higher pH, P (phosphorus), N (nitrogen), K (potassium), Mg (magnesium), Zn (zinc), Mn (Manganese), B (boron), as well as the cation exchange capacity and some exchangeable cations, such as, Na^+ (sodium ions), K^+ (potassium ions) and Mg^+ (magnesium ions). The compost treatment resulted in significantly higher Ca (calcium) and Ca^+ (calcium ions) in the heavier soil compared to the other treatments. The organic mulches, including the woodchips treatment, consistently resulted in higher mineral levels and therefore performed the best in this regard and did so in the heavier soil. In contrast to the heavier soil, none of the treatments were successful in ameliorating the nutrient status of the lighter soil, with the exception however of the increased percentage C as a result of the compost and vermi-castings treatments.

The compost treatment realised consistently higher mychorrizael colonization in both sites, however, not always significantly higher than the other treatments. The vermi-castings treatment realised consistently lower plant parasitic nematodes numbers. Higher free-living nematodes were also frequently realised during both seasons and in both sites. The organic mulches therefore proved promising with regard to soil biota.

The organic treatments, with the exception of the vermi-castings treatment, resulted in improved root number and distribution in the heavier soil. The vermi-castings treatment

resulted in a superior root environment and did not need to enhance its root system in order to achieve good fruit yield and quality. In contrast, the geotextile fabric treatment performed better in this regard in the lighter soil. The geotextile fabric treatment also achieved the lowest weed counts, quantified as winter weeds, in both sites. Yield efficiency, in the heavier soil, and the incidence of sunburn in both sites, were influenced by mulching. In the heavier soil, the woodchips treatment resulted in the highest yield efficiency and the compost treatment consistently resulted in the highest incidence of sunburn. In the lighter soil the control treatment resulted in the highest incidence of sunburn. The vermi-castings treatment consistently resulted in lower incidences of sunburn.

Due to the limited quantification of irrigation in this trial, the consequence of irrigation on different mulches was not evaluated and should be considered for future research.

OPSOMMING

‘n Ondersoek na die effek van verskillende deklae op die wortelomgewing, insluitende fisiese, chemiese en biologiese grond faktore, is uitgevoer as ‘n veldproef of twee verskillende grondtipes, op ‘Cripps’ Pink’ appels. Drie organiese deklae is ge-evalueer naamlik: kompos, ‘vermi-castings’ en houtspaanders, asook ‘n anorganiese geotekstiel materiaal deklaag, en vergelyk met ‘n kontrole van skoon bewerking.

Die organiese behandelings het verbeterde fisiese kondisies (laer bulkdigtheid) in die swaarder grond, asook ‘n verlaging in temperatuur fluktuasies en algemene verhoging in grondtemperature gedurende die seisoene in beide persele tot gevolg gehad. Die geotekstiel behandeling het verhoogde grondvog-vlakke in die boonste 40 cm in beide persele tot gevolg gehad, alhoewel dit meer prominent in die swaarder grond was. In sanderige grondperseel, het die kompos behandeling hoër grondvog-vlakke in die boonste 40 cm getoon as die ander behandelings.

Die ‘vermi-castings’ behandeling het die beste resultate in terme van verbetering van nutrient- vlakke in die swaarder grond behaal. Dit het ‘n betekenisvol hoër pH, P (fosfaat), N (stikstof), K (kalium), Mg (magnesium), Zn (sink), Mn (mangaan), B (boron), katioon uitruilings kapasiteit en sommige uitruilbare katione soos , Na^+ (natrium ione), K^+ (kalium ione) en Mg^+ (magnesium ione) as die ander behandelings in die swaarder gehad. Die kompos

behandeling het betekenisvol hoër Ca (kalsium) en Ca^{+} (kalsium ione) in die swaarder grond getoon. Die organiese behandelings, insluitend die houtspaander behandeling, het dus in die geval, konstant die beste resultate te opsigte van hoër nutriënt vlakke in die swaarder grond getoon. Inteenstelling met die swaarder grond, het geen behandling daarin geslaag om die grondvoedingstatus van die sanderige grond te verbeter nie, met uitsondering die verhoogde persentasie C as ‘n resultaat van die kompos en ‘vermi-castings’ behandelings.

Die kompos behandeling het konstant hoër mychorriza-kolonisasie teweeg gebring in beide persele, alhoewel nie altyd betekenisvol hoër as die ander behandelings was nie. Die ‘vermi-castings’ behandeling het konstant ‘n laer persentasie plant-parasitiese nematodes getoon. Meer vry-lewende nematodes het ook gereeld oor die totale vier jaar wat die volledige proef gestrek het, op beide persele, voorgekom. Die organiese deklae toon dus belowende resultate in terme van biota.

Die organiese behandelings, met uitsondering van die ‘vermi-castings’ behandeling, het verhoogte wortel ontwikkeling en -verspreiding in die swaarder grond tot gevolg gehad, Die ‘vermi-castings’ behandeling het ‘n besondere goeie wortelomgewing geskep en ‘n verbetering in die wortelstelsel om ‘n goeie opbrengs en kwaliteit te behaal, was nie nodig nie.

Daarinteen het die geotekstiel behandeling beter resultate in die meer sanderige grond behaal. Die geotekstiel behandeling het ook die laagste onkruidstand in beide persele gehad. Opbrengs, in die swaarder grond, en die voorkoms van sonbrand in beide persele, is beïnvloed deur die dekgewasse. In die swaarder grondperseel het die houtspaanders behandeling die hoogste opbrengs getoon en die kompos behandeling, konstant die hoogste voorkoms van sonbrand. In die ligter, sanderige grondperseel, is die hoogste sonbrand voorkoms gemeet in die kontrole behandeling. Die ‘vermi-castings’ behandeling het die laagste sonbrand voorkoms getoon.

Weens die beperkte kwantifisering van die besproeiing in die proef, is die gevolge van besproeiing op verskillende deklae nie ondersoek nie en behoort dit oorweeg te word in toekomstige navorsing.

DEDICATION

Dedicated to my mother and brother

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This thesis presents a consolidation of manuscripts where each paper is an individual entity. Some repetition between chapters has therefore been unavoidable.

General Introduction

Due to the ever changing, variable and fragile environment, fruit producers all over the world are continually seeking sustainable ways to improve production, the basis of which begins at root level. The tree's performance relies considerably on root systems that are well developed, efficient, and flexible to changing soil environments (Giulivo 1990). Soil properties must therefore be favourable to the tree's needs in order for the tree to create such root systems. Many fruit growers are leaning towards integrated fruit production methods in an attempt to reduce costs as well as harmful and destructive inputs into the environment (Merwin et al. 1995; Neilsen et al. 2004; Treder et al. 2004). Mulching has proved to be advantageous in developing and improving root systems, without impacting the environment negatively, and can therefore play a fundamental role in integrated fruit production.

Enhanced physical, chemical and biological properties of the soil are attributes of mulching resulting in superior root growth. Traditionally, mulching is used for soil moisture conservation and the buffering of damaging, fluctuating soil temperatures, both of which are aimed at improving the root environment (Baver et al. 1972; Haynes 1980; Janick 1986; Lanini et al. 1988; Wolstenholme et al. 1996; Pregitzer et al. 2000). In addition, certain mulches have proved to preserve the soil's physical nature (Turney and Menge 1994), alter and enhance the soil's chemical status (Haynes 1980; Giulivo 1990; Wolstenholme et al. 1996), and create a more habitable environment for soil flora and fauna (Lakatos et al. 2001; Nagy et al. 2008).

With all of the above mentioned benefits mulching can achieve regarding the root environment, fruit yield and quality can be greatly enhanced (Lang, et al. 2001 Szewczuk and Gudarowska, 2004). The motivation behind this thesis was to determine whether different mulches, on different soil types, could improve the root environment, resulting in better root growth and functioning, and ultimately improved fruit yield and quality.

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Literature Review

Introduction

Fruit growers are constantly striving for increased yield and quality, which starts at root level. Optimal acquisition and use of resources is vital in maintaining the correct balance of growth and development between roots, shoots, and fruiting in orchards. Root systems must be well developed, efficient, and flexible to adapt to changing soil environments in order to fulfil their functions in a variety of environmental conditions and ensure the tree's overall performance as a quality fruit producer (Giulivo 1990).

Roots function as anchors to the plant, as well as acquiring and transporting nutrients and water from the medium in which they are grown to the shoots (Giulivo 1990; Bingham and Robinson 2003). In addition, they are sites of hormone biosynthesis and are important sinks for the storage of carbohydrates synthesised by the plant via photosynthesis (Aung 1974). Optimal root growth and development is therefore essential for good plant growth and production of fruit trees.

Root growth is controlled genetically, as well as by the amount of assimilates supplied by the canopy (Giulivo 1990), however, the soil environment also plays an important role. The soil environment is capable of offering a good habitat for root growth as it can provide the necessary environmental factors important for root growth and development. These factors include; soil physical properties, soil temperature, soil water content and availability, oxygen and carbon dioxide levels in the soil, soil organic content, nutrient availability and mycorrhizae colonization of the roots (Taylor 1974; Nielsen 1974; Newman 1974; Stolzy 1974; Adams 1974; Gerdemann 1974). All of these factors constitute the chemical, physical and biological properties of the soil. Soil management and groundcover management techniques can have a profound influence on these properties, which results in an improvement in root growth and development, and ultimately an improvement in health and quality of the orchard (Tisdall 1989).

With growing concerns regarding preservation of the environment, many fruit growers are leaning towards integrated fruit production techniques, in an attempt to reduce costs as well as harmful and destructive inputs into the environment (Merwin et al. 1995; Neilsen et al. 2004; Treder et al. 2004). The use of ground covers for the improvement of root distribution and density can form part of a successful integrated fruit production system.

Ground cover use is the application of a layer of suitable material, living or dead, to the soil surface to minimise tree stress and improve the root environment (Wolstenholme et al. 1996). It is a well known practice in horticulture, with the obvious function of reducing soil water loss by evaporation, thereby allowing more efficient and economical use of water (Treder et al. 2004; Nagy et al. 2008). In addition, ground covers create favourable microclimates for the fruit trees (Varga et al. 2004), as well as, controlling weeds and thus reduce competition for water and nutrients (Cross et al. 1993; Fourie et al. 2011).

In many parts of the world insufficient precipitation and rising temperatures are the main limiting factors in crop production. Water availability and temperature are the primary climatic factors determining geographic plant distribution (Nielsen 1974). Reduced soil water content decreases root uptake of water and nutrients and thus adversely affects fruit yield and quality (Treder et al. 2004). Extreme soil temperatures have been recorded in areas of crop production and can limit root growth or even kill existing roots (Tisdall 1989). Ground covers are successful in regulating soil water and temperature (Nielsen 1974; Giulivo 1990; Wolstenholme et al. 1996).

As mentioned, by reducing the amount of inputs needed for the production process, the grower will be reducing the impact made on the environment. The use of ground covers has shown to have a positive effect on the nutritional and biological status of the soil (Nagy et al. 2008). Certain organic ground covers add nutritional value to the soil as well as promote healthy microorganism populations that are beneficial to the root environment (Lakatos et al. 2001). In addition, ground covers are able to alter the soil's physical properties, including aeration.

This review looks at the environmental factors important for root growth, development, distribution and density; and the influence ground covers have on these factors.

Soil physical properties as a factor influencing root growth and development

The soil's physical properties greatly influence root elongation and growth through the soil. Soil structure and strength are important aspects of a soil, which encompass properties such as bulk density, porosity, texture, pedality, soil pressure, all of which have bearing on the behaviour of growing roots (Taylor 1974).

Hillel (1980) defines soil structure as "the arrangement and organization of particles in the soil." Primary particles (sand, slit, and clay) cluster and bind together by organic matter and clay, to form secondary particles (clods, crumbs, and peds). This forms the structural pattern of the soil (Haynes 1980). Soil strength is defined by Hillel (1980) as "the maximal stress which can be induced in a given soil body without causing the body to fail."

Root growth and development in response to soil physical properties

The soil provides an external resistance to the growth and elongation of roots (Taylor 1974). The meristematic cells, which are located in the meristematic zone of the root tip, divide and elongate, pushing the root forward through the soil (Taiz and Zeiger 2010; Taylor 1974). The division of these cells is directed towards the root base as well as the root apex, where a root cap is formed (Taiz and Zeiger 2010). The root cap functions as a shield to the fragile meristematic cells as the root moves through the soil (Taiz and Zeiger 2010). The driving force of cell elongation, and thus root movement through the soil, is the turgor pressure in the elongating cells. This turgor pressure must be great enough to push the root through the constraints of the surrounding soil, which in turn determines the rate of cell elongation (Taylor 1974).

Soil fabric or matrix has great bearing on root growth and development as it influences other factors that are important for root growth, such as soil water, soil temperature, soil aeration and soil strength (Hillel 1980; Taylor 1974). Soil fabric, as defined by Hillel (1980), is "the manner in which the various particles are packed and held together in a continuous spatial network." In a study performed by Taylor and Ratliff (1969), where soil strength was measured by a penetrometer, an increase in soil strength around the root resulted in a decrease in the rate of root elongation of peanut (*Arachis hypogaea)* roots. It is therefore evident that soil strength has an impact on root growth.

When roots navigate through the soil they either penetrate voids and large pore spaces, or root tips exert enough pressure to move soil particles to the side as they move past (Haynes 1980; Taylor 1974). In doing this they change the pore size distribution of their soil environment (Russell 1971 ref. by Haynes 1980). Soils of high strength greatly limit root growth, as soil particles are not easily moved aside (Taylor 1974). Root growth and elongation can, however, overcome soils of high strength, provided there are sufficient voids and pores large enough for roots to grow through (Taylor 1974). If pore spaces become too small, root growth becomes limited. Soil compaction therefore poses a problem for root penetration. Compacted soils are associated with a reduction in pore size, an increase in soil strength, an increase in bulk density, and a reduction in soil aeration (Taylor 1974) and can therefore seriously limit agricultural practices in certain areas.

Structural discontinuities in the profile play a huge role in the distribution of roots (Taylor 1974). Cracking in the profile, strong ped development, and the presence of pans in the profile influence rooting patterns and distributions. Roots tend to grow through cracks in the soil, providing an easy path through a potentially impenetrable soil. Roots also tend to grow around peds and through voids created by adjoining peds (Taylor 1974). Peds/aggregates are a type of soil structure explained by Hillel (1980), where "soil particles are associated in quasi-stable small clods." Due to the formation of voids by adjoining peds, soils rich in this type of structure are the most desirable soils, structure wise, for root growth (Hillel 1980). The presence of pans in the soil is, however, an unfavourable limitation in the soil. Roots are diverted horizontally, on top of the pan as penetration through the pan is too difficult. This is due to the high soil strength of the pan (Taylor 1974). It may be the case that a crack develops in the pan, in which case a root is able to penetrate the pan (Taylor 1974). If pans occur deeper than the plant's potential rooting depth, root growth is not limited (Taylor 1974). Shallow pans, however, pose a problem as root growth is then restricted to the top few centimetres above the pan and are therefore at risk of desiccation as roots cannot tap deeper soil for water and nutrients (Taylor 1974). In addition, water collection above the pan can result in dire consequences for root growth as the roots will be unable to grow and develop due to anaerobic conditions (Stolzy 1974; Taylor 1974).

In addition, root distribution is also largely influenced by soil texture, which refers to the size of soil particles (Hillel 1980). Sand, silt and clay make up the major textural fractions of the soil (Hillel 1980). Coarse textured soils are soils with a high sand fraction, and fine textured soils are soils with a high clay fraction. Aggregation is significantly influence by soil texture, which in turn influences root distribution (Bronick and Lal 2005). Aggregation is affected by clay and the swelling and dispersing properties there of. Disaggregation occurs due to the swelling and shrinking of a clayey soil. Soils poorly aggregated are not as desirable as soils richly aggregated, as they do not provide as many voids and pores for roots to penetrate. Roots therefore do not move through poorly aggregated soil with as much ease as they would if they were in a richly aggregated soil. Clay soils can therefore have a limiting effect on root growth. Loamy soils contain balanced proportions of coarse and fine particles and are frequently considered as good mediums for plant growth and agricultural practices (Hillel 1980). In broad terms, they encompass the aggregation properties of a sandy soil, as well as the water and nutrient holding abilities of a clayey soil (Hillel 1980). Roots can therefore grow and distribute more evenly through the profile and have sufficient accesses to water and nutrients.

It is therefore evident that soil structure and soil strength play a vital role in the growth, elongation, and distribution of roots. Structural limitations in the soil can divert roots in completely new directions, but structural discontinuities can also provide paths through soils that might otherwise be limiting for growth. Importantly, the rate of root growth and elongation can be greatly decreased as soil strength increases (Taylor 1974).

The influence of ground covers on soil physical properties

Ground covers affect the structure and strength of the soil near the surface. With the use of living ground covers in orchards, the roots of the grass are able to alter the soil structure and strength in the same way as the orchard tree roots do (Haynes 1980). Like tree roots, grass roots also create channels and move soil particles (Haynes 1980). With the death of grass roots, channels are maintained due to the stabilization of the channel walls by bacterial gums which are produced with the decomposition process (Russell 1971 according to Haynes 1980). Earthworm activity is also encouraged with grass cover, and with the worm's burrowing nature, pore spaces are created and altered (Haynes 1980). Additionally, the polysaccharide gums produced by microorganisms in the rhizosphere of the grass roots, and the secretion of mucigel (gelatinous material) by the grass root tips (Taiz and Zeiger 2010), have stabilizing effects on the soil structure (Haynes 1980). Living ground covers therefore greatly influences structural pore spaces and the stability of soil structure (Haynes 1980), which is maintained with residues from roots exudates after the ground cover dies. However, roots from the cover crop may compete with the tree roots for open voids and channels, thus limiting the growth and distribution of the tree roots.

Ground covers can encourage increased root length and density to greater depths by influencing the soil's physical properties. Lang et al. (2001) investigated the use of mulches as a tool to enhance apple fruit storage in New Zealand. The mulch that was used was black polyethylene topped with sawdust. It was observed that root length density was greater, and extended deeper in the profile under mulched surfaces as apposed too un-mulched surfaces. This was attributed to an overall more favourable soil environment (encompassing soil physical properties, temperature and water) created by mulching the soil surface. As a result soil micro fauna and flora were positively influenced, favouring the soil's physical properties, which allowed for increased root length density and rooting depth.

Organic and fabric ground covers are known to increase water infiltration into the soil by decreasing runoff, as well as altering the soil structure in ways that make water infiltration easier. They absorb the water drop impact on the soil during rain or irrigation (Haynes 1980), which prevents crusting taking place on the soil surface, and in turn results in decreased runoff and erosion (Lal 1978 according to Haynes 1980). Due to the protective covering offered by ground covers, soil compaction is also avoided. By covering the soil, it is left less vulnerable to elements that can cause soil structure breakdown or increase soil strength. Ground covers therefore contribute to the maintenance of structural stability in the soil, and thus influence physical characteristics of the soil (Haynes 1980).

Temperature as a factor influencing root growth and development

Roots are very sensitive to soil temperatures. Temperatures in the soil can fluctuate considerably on and near the soil surface, depending on the extent of soil coverage by plants and ground covers (Pregitzer et al. 2000). Temperature fluctuation intensities decrease down the profile, with extreme temperature fluctuations in the root zone being detrimental to the growth and development of roots. Most of the fine feeder roots occur near the soil surface and are extremely vulnerable to inconsistencies in soil temperature (Pregitzer et al. 2000). Ground covers help maintain a habitable root environment by decreasing the degree of temperature fluctuations.

Root growth and development in response to soil temperature

Root growth increases with increasing soil temperatures up to a point, at which the root's optimum growth temperature is reached. Beyond this point root growth rates decrease and mortality rates increase. Different plant species have different optimal root growth temperatures (Pregitzer et al. 2000). Optimal temperatures vary for different developmental and maturation stages of the roots. Root growth and development of a specific plant can therefore have many different optimal temperatures depending on the growth stage of the roots, all of which are equally important and affect nutrient and water uptake (Nielsen 1974). For example at lower temperatures, new root formation is promoted, whereas at higher temperatures, root branching is encouraged. It has also been found that much of the root growth is initiated at temperatures below the optimum (Nielsen 1974). The duration of exposure of roots to certain temperatures has a big influence on root behaviour, regardless of whether temperatures are optimal or not.

The initiation and cessation of root growth is largely determined by soil temperature. In addition, cell and root elongation, root thickness, new lateral root initiation, and patterns and root branching habits are also influenced by soil temperature (Kasper and Bland 1992; McMichael and Burke 1998). Both controlled studies and field studies have shown that roots grow more rapidly at higher temperatures, provided all the other growth factors are not limiting (Pregitzer et al. 2000). Roots are less branched, wider in diameter and whiter in colour when temperatures are lower, and in cold conditions, roots become elongated and maturation is stunted (Nielsen 1974). Nielsen (1974) states that roots become filamentous when they are exposed to higher temperatures. At high temperatures root length is also stunted and individual root life span is limited (Pregitzer et al. 2000). Due to warmer conditions near the surface, more fine feeder, branched roots will occur, decreasing down the profile as conditions get cooler. Individual root diameter increases down the profile with the decrease in number of roots. The morphology and distribution of the roots in the profile is therefore highly dependent on temperatures down the profile and the root zone area is largely determined by soil temperature distribution (Nielsen 1974).

Soil temperature is often linked to other factors that influence root growth and development, such as soil water content, nutrient availability and microbial activity. Conditions that result in plant water stress often occur in times of high temperatures (Zak et al. 1999), and in this case, root growth does not increase with temperature increases, as the soil water status is the limiting factor (Pregitzer et al. 2000). However, this is largely dependent on the type of plant as some plants respond to drought stress by increasing their root systems in an effort to tap larger volumes of soil for water (Pregitzer et al. 2000). With increasing soil temperatures, come changes in microbial activity and thus mineral availability. For example Zak et al. (1999) found that the mineralization of nutrients, such as nitrogen, that are bound organically increases with increasing temperatures. This is as a result of the increase in activity of the microbes responsible for the mineralization process due to increasing temperatures (Zak et al. 1999).

Root growth flushes and mortality are highly dependent on seasons and therefore occur at certain times of the year. Pregitzer et al. (2000) mentions that this sort of patterning is associated with canopy coverage and development. With the development of a full canopy in spring comes an important period of root growth. In contrast, the senescence of a canopy in autumn corresponds to a period of root mortality. Growth flushes are fed by the amount of stored carbohydrates as a result of the previous season, as well as current photosynthates, supplied by actively photosynthesising leaves (Pregitzer et al. 2000). Taking all of the above mentioned into account, the strong spring root flush experienced by deciduous fruit trees, therefore takes place in relatively cool soils. However, it can be argued that the root flush lags behind bud break and shoot growth in the spring, as it requires higher soil temperatures than what is present at that time (Pregitzer et al. 2000). If this is the case, it would mean that shoot and root meristems genetically react in the same way during rising temperatures in the spring (Pregitzer et al. 2000). It is important to then consider global warming and the effect it may have on soil temperatures and ultimately on root flushes. It can be hypothesised that with increasing temperatures, root flushes will take place earlier in the year (Pregitzer et al. 2000).

Root respiration is also linked to soil temperature. Pregitzer et al. (2000) reports that root respiration rates increase with increasing temperatures and that it is of an exponential relationship. The Q_{10} values for tree root species often lie between 2 and 3. Root respiration is also closely linked to soil water and nutrient availability and uptake, and all of these factors have the ability to change in the field and result in changes in root respiration rates (Pregitzer et al. 2000).

Soil temperature is therefore an important factor in determining and regulating root growth and development, and is closely linked to other factors necessary for roots as functioning organs of the plant.

The influence of ground covers on soil temperature

Root behaviour is very sensitive to small changes in temperature and if unfavourable temperatures persist for a period of time irreversible damage to the roots can occur. The use of ground covers is often very effective in modifying and ameliorating the effects of extreme temperatures (Janick 1986).

Ground covers have buffer like characteristics with regards to changing temperatures. Mulches are often insulating substances (Janick 1986) and with the inclusion of other forms of ground covers, they provide protective coverings for the soil from extreme temperatures. Covered soils experience decreased temperature fluctuations, and thus contribute to a more mesic soil environment (Lanini et al. 1988). This is partly due to the improved soil water status, which keeps the soil at a more constant temperature (Lanini et al. 1988) and as a result of their insulating, shading and heat absorbing properties (Janick 1986). The insulating property of ground covers conserves ground heat and prevents soil temperatures form getting too low in the cold months or too high in hot months. They buffer and stabilize soil temperatures preventing extreme fluctuations that can harm and damage the roots (Janick 1986). A covered surface therefore keeps the roots warm under freezing conditions and cool under sudden hot spells.

In a study by Treder et al. (2004), in Skierniewice, Poland, on the response of young apple trees to different orchard floor management systems, a mulch of 20 cm wood chips was applied on the soil surface. It was found that in the winter months, soil temperatures in the top 10 cm were higher under the mulched surfaces than in control plots (un-mulched surfaces). With an air temperature dropping to -22.1°C, soil temperatures in control plots dropped to -5.7°C, where as in mulched plots, temperatures only dropped to -0.4°C and were very stable regardless of fluctuating air temperatures. They also found that, in summer, soil temperatures of mulched plots where slightly higher than in control plots due to heat conservation as a result. They concluded that mulching reduced fluctuations in soil temperature, particularly in winter, and reduced the impacts of extreme cooling and freezing conditions.

Fourie and Freitag (2010) conducted a study on the influence of ground covers on soil temperatures in vineyards in the Breede River Valley wine region. From their findings they were able to conclude that surface mulching of a medium textured soil reduced the diurnal variation in temperature during the growing season. A straw covered surface lagged one week behind soils that were subject to other management practices, in reaching temperatures that are favourable to soil organism activity which ultimately make nutrients more available to the roots. In addition, they also found that bud break was slightly delayed in the treatments that received straw cover. With the use of a cover crop, which was eradicated just before grapevine bud break, as well as a full surface straw mulch, suboptimal temperatures were avoided during the first two weeks of bud break. Ultimately they concluded that throughout the growing season, mulching created a favourable root environment for the grapevine roots.

Soil organic content and nutrient availability as factors influencing root growth and development

In order for the roots to fulfil one of their primary functions as acquirers of nutrients, the organic matter and nutrient status of the soil is of paramount importance to root growth and must be in sufficient quantities. As with all of the growth factors mentioned in this review being closely linked to each other, soil organic matter content and nutrient availability is no different. With regard to the use of ground covers, their fundamental purpose is not usually aimed at nutrient input into the soil.

However, organic covers decompose over time and can release nutrients and increase the organic matter content of the soil (Wolstenholme et al. 1996).

Root growth and development in response to soil organic content and nutrient availability

The uptake of nutrients by roots is significantly affected by soil water, temperature and aeration (Giulivo 1990). Soil water provides the medium in which nutrients are transported and taken up, and makes up the soil solution. Adams (1974) defines soil solution as “the soil water and its dissolved electrolytes plus small quantities of dissolved gases and water-soluble compounds.” Soil aeration has an impact on the amount of nutrients that are in the gaseous phase, such as nitrogen (Giulivo 1990). Solid or gaseous phase nutrients are dissolved in the soil solution before they are transported or taken up by the plant (Giulivo 1990). The soil solution is therefore the medium in which most of the chemical reactions occur in the soil (Adams 1974).

Soil organic matter content is very important for root growth, as limiting factors in the soil, such as decreased soil porosity and aeration, are greatly improved by increased organic matter content (Giulivo 1990). Organic matter content in the soil increases porosity, aeration, water holding capacity, and cation exchange capacity, all of which, make the soil more habitable for roots (Giulivo 1990). With an increase in all of these factors, roots are able to mine and take up nutrients from the soil more effectively. Organic matter therefore contributes to optimal nutrient uptake by the roots.

The root/shoot ratio of trees is significantly influenced by the soil’s nutrient status and availability. Giulivo (1990) mentions that soils with high nutrient and water availability result in augmented shoot growth in comparison to root growth. He attributes this to an increase in biomass and assimilation rates of the shoots and a decrease of the fine roots. A profusion of available nutrients in the soil thus means that the rate of shoot growth exceeds the rate of root growth resulting in a plant with a relatively small root system (Taiz and Zeiger 2010). It must be noted that the availability of other resources and factors, such as light intensity in the orchard and crop load, also influences the assimilation rate of the foliage and contributes to the root/shoot ratio (Giulivo 1990).

The efficient uptake of nutrients from the soil is greatly dependent on the root system and its conformation, structure and development (Giulivo 1990). Soil water and nutrient status are closely linked as far as shaping the root system and efficient uptake is concerned. In order for the plant to acquire and transport nutrients, the roots must be sufficiently hydrated which results from adequate soil water (Giulivo 1990). The root system and patterning is influenced more by soil water than soil nutrient status. However, nutrient levels have the same effect on changes in root growth, as with the case of water availability, and are as a result in nutrient availability (Giulivo 1990; Pregitzer et al. 2000). Pregitzer et al. (2000) attribute the increased rate of root length extension to an increase in the amount of available nitrogen levels in the soil. It must, however, be mentioned that an increase in soil temperature can be linked to the availability of nitrogen in the soil, as nitrogen is mineralized faster at higher temperatures (Pregitzer et al. 2000). This illustrates the importance of different growth factors, and their association and interaction in the growth and development of roots.

The rhizosphere is the small volume of soil around the surface of roots where nutrient uptake takes place. It is defined by Taiz and Zeiger (2010) as “the immediate micro environment surrounding the root.” Poor nutrient status in this region results in decreased root growth (Taiz and Zeiger 2010). Different nutrients are absorbed in different regions of the root. Absorption takes place in the apical regions and/or over the entire root, depending on the plant species, the nutrient being absorbed and root maturity (Giulivo 1990; Taiz and Zeiger 2010). In the apical regions of the root, the nutrient demand in the tissue is very high, resulting in a strong driving force for the uptake of nutrients in the region (Taiz and Zeiger 2010). This is the reason for the majority of nutrient uptake occurring in the apical root zone. Active root growth is therefore very important for the effective uptake of nutrients. The soil-root contact thereof is vital for nutrient uptake and it must be maintained (Giulivo 1990).

The uptake of different nutrients contributes to the growth and development of the roots in different ways. With the sufficient uptake of nutrients such as potassium, chloride, and nitrate, effective cell elongation occurs and results in an increased osmotic potential in the cell (Taiz and Zeiger 2010). This is very important for the elongation zone in the root.

Roots mainly take up nitrogen in the form of ammonium. Taiz and Zeiger (2010) explain "Ammonium is the preferred nitrogen source to support cell division in the meristem because meristematic tissues are often carbohydrate-limited and because assimilation of ammonium into organic nitrogen compounds consumes less energy than assimilation of nitrate." Carbohydrate-limited tissue, referring to tissues that act as sinks for carbohydrates formed in the photosynthesising leaves, and thus do not contain sustained energy to account nitrate assimilation. Cell division is the basis of any growth and therefore the uptake of ammonium is of vital importance to root growth and development.

The depletion of certain nutrients can result in unfavourable consequences for the roots and ultimately the entire plant. Due to the nature of the movement of the soil solution through the soil (discussed later), depletion zones can occur due to the uptake of the immediate solution around the root (Giulivo 1990). Well spaced rooting is therefore important in preventing the implications of depletion zones (Giulivo 1990). In addition, roots have other strategies in place assisting them in avoiding zones of depletion. As the nutrients in the soil around the roots become depleted, the root hairs and the root apex change direction and grow into regions of available nutrients (Taiz and Zeiger 2010).

Nutrients can also be present in excess quantities in the soil, making the soil saline. Saline soils can limit growth if they are in quantities that reach toxic levels of the particular nutrient for a particular plant, or in quantities that influence water availability (Taiz and Zeiger 2010). If water deliverance to the soil is in not limiting, salts such as sodium sulphate and sodium chloride, that are common in saline soils, are leached out of the root zone and do not pose a problem for root growth (Taiz and Zeiger 2010). Heavy metals such as copper, zinc, nickel, mercury, silver, chromium, cobalt and led can also accumulate in soils, causing toxicities in plants (Taiz and Zeiger 2010). It is important for entire plant growth that certain mineral ions do not accumulate in excess quantities.

The pH of soils also effects root growth. Root growth generally prefers slightly acidic soil solutions, ranging between 5.5 and 6.5 (Taiz and Zeiger 2010). This is, however, highly dependent on the plant species and climatic conditions. Nutrient availability is largely determined by soil pH due to the promotion of rock weathering and the increase in solubility of certain nutrients in acid conditions (Taiz and Zeiger 2010). In acidic conditions potassium, magnesium, calcium and manganese ions are released as a result of the weathering process, as well as increased solubilities of carbonates, sulphates and phosphates (Taiz and Zeiger 2010). These nutrients are thus made more available to roots and an increase in root growth therefore occurs. However, the leaching of exchangeable bases, such as calcium and magnesium, out of the root zone is accompanied by a decrease in the soil pH (Haynes, 1980). Not only are exchangeable bases made unavailable to the roots, toxicities of elements such as manganese can occur in acidic conditions (Haynes 1980).

The influence of ground covers on soil organic content and nutrient availability

Ground covers are not primarily used for soil nutrition, however, some covers can contribute and have an influence on the soil's nutrient status. The cation exchange capacity of the soil is increased by the formation humus which is the end product organic matter of decomposition (Wolstenholme et al. 1996). Organic ground covers successfully maintain the humus content of the soil, resulting in the upper centimetres of the top soil being very high in organic matter (Haynes 1980). The organic matter content of the soil is of particular importance to the structure of the soil (Haynes 1980). With an increase in the cation exchange capacity, more nutrients are held in the soil and are available for root uptake and less are leached away.

It has been shown that roots take up nitrogen in the form of ammonium and therefore it is important that there is sufficient ammonium in the soil for the plant's use (Taiz and Zeiger 2010). When nitrogen is released due to the decomposition process it is in the form of ammonium (Maynard 1989; Taiz and Zeiger 2010). Ammonium is either taken up by the roots, or it is adsorbed to clay and humus particles and can become available to the plant at a later stage (Maynard 1989). Ammonium can, however, also be nitrified to form nitrate (Taiz and Zeiger 2010; Maynard 1989). Nitrate is more prone to leaching and with excessive nitrate leaching, groundwater can become polluted (Maynard 1989). The nitrification of ammonium to nitrate does not pose a huge problem with regard to nitrogen entering the soil from organic matter, as it is released very slowly and thus reduces the risk of nitrification and leaching taking place (Maynard 1989). Organic ground covers with low carbon:nitrogen (C:N) ratios reduce the need for the application of inorganic nitrogen fertilizers in the orchard (Maynard 1989).

Soil microorganisms help with the decomposition of organic mulches and their populations can increase with the application of certain covers (Wolstenholme et al. 1996). However, covers with high C:N ratios do not provide enough nitrogen for the microorganism population and the plant, and extra nitrogen is required and supplied by the soil (Handreck and Black 1994). This may result in a depletion of nitrogen in the soil and to the tree roots and is referred to as a nitrogen 'draw-down' or 'negative period' (Handreck and Black 1994; Turney and Menge 1994). Table 1, modified from Handreck and Black (1994), indicates the percentage nitrogen contents and the C:N ratios of various mulching materials. When these ratios are higher than 100, such as uncomposted bark and sawdusts from cellulose rich wood, mulches result in low nitrogen input into the soil (Handreck and Black 1994). Uncomposted South African pine bark was found to have a ratio of up to 450. The ratios of bark mulches can be reduced to approximately 30 with proper composting methods (Handreck and Black 1994).

Table 1. Percentage nitrogen contents and C:N ratios of various mulching materials (modified from Handreck and Black 1994)

Material	**% N in Dry Matter**	**C:N Ratio**
Pinus radiata sawdust	0.09	550
Cardboard	-	500
Pinus radiate bark	0.1	500
Eucalyptus sawdust	0.1	500
Eucalyptus bark	0.2	250
Paper	0.2	170
Bagasse	0.4	120
Woody prunings	-	100
Composted eucalyptus sawdust	0.45	100
Composted *P. radiate* bark	0.4	100
Wheat or oats, straw	0.4	100
Mature leaves	0.7	60
Composted pine bark	1.1	30-40
Maize stalks	1.2	33
Peat	1.5	30

Grasses	1.8	22
Mixed weeds	2.0	19
Cow manure	2.6	15
Lucerne hay	3.1	13
Peanut shells	4.4	12
Poultry litter	2.41	10-11
Poultry droppings	5.5	7
Pig manure	-	5
Urine	-	2

Phosphorus, calcium and boron have been found to increase under organic mulches (Wolstenholme et al. 1996). These elements are particularly important for healthy and vigorous root growth (Wolstenholme et al. 1996). Composted pine bark has shown to be a good source of potassium and boron (Wolstenholme et al. 1996), whereas livestock manure and straw are good sources of phosphorus and potassium (Lakatos et al. 2001). Although, these materials decompose quickly, this often leads to leaching of these elements as well as nitrate (Lakatos et al. 2001). Livestock manure, however, can also lead to a build up of phosphates in the soil which can result in toxicities (Handreck and Black 1994; Turney and Menge 1994).

St. Laurent et al. (2008) studied the effect of long term orchard management systems on soil microorganisms, apple replant disease and soil nutrient. The ground cover management systems used were: (1) post-emergence herbicide with the application of glyphosate in May and July each year, (2) pre-emergence herbicide where bare soil strips were maintained by applying tank-mixed glyphosate, norflurazon and diuron herbicides annually, (3) mowed sod grass, (4) bark mulch and (5) grass maintained in the work row in between tree rows. After 14 years under the five different orchard ground cover management systems, the treatment where the soil received a bark mulch exhibited significant increases in calcium, iron, manganese and phosphorus levels. Iron and aluminium availability was higher in the grass lane and the sod grass soils in comparison to the herbicide treated soils. They also found that organic matter content under the mulched surface almost doubled in quantity, and the soil under the grass lane had significantly more organic matter than the remaining three treatments. Although these findings were observed in relation to microorganism populations, they give a clear indication of the effect of ground cover systems on the soil's nutrient and organic matter content in comparison to other orchard floor management systems.

Merwin et al. (1995) conducted a study comparing different ground cover management systems in young apple orchards on two different soil types in New York: a silt loam site and a gravelly silt loam site. The ground cover management systems that were analysed were: (1) Weed mat, (2) Agri tex geotextile fabric, (3) Wood chip mulch (10cm depth), hay mulch (10cm depth), (4) Herbicide and (5) Synthetic mulch (perforated black polyethylene and non-perforated white polyethylene). After a three year period, the extractable soil nutrients were analysed. In the silt loam site accumulation of certain nutrients as a result of the treatments was as follows; NO_3^-, manganese, boron, iron and zinc were found to be higher in soils where herbicides were applied than soils under the synthetic mulches. Potassium and phosphorus concentrations were higher in soils treated with herbicides and woodchip mulches than soils under synthetic mulches. In the gravelly silt loam site accumulation of certain nutrients as a result of the treatments was as follows; NO_3^-, magnesium and potassium concentrations were higher in hay mulched soils than soils with herbicide application and other mulches. Magnesium, iron and boron were lower in soils with woodchip mulches than the other treatments. In addition, they found that soil organic matter content did not differ between different soil management systems.

In the study by Lang et al. (2001) to investigate the use of mulching to increase apple fruit storage, a combination of mulching and surface gypsum application was used. They found that with this combination, higher concentrations of calcium, potassium and magnesium in the upper soil profile resulted in the mulched soils as appose to un-mulched soils. The cation exchange capacity was also higher in mulched soils. In addition, mulching stimulated fine root growth. With increased feeder roots and minerals, an increase in leaf calcium and potassium (not magnesium) levels was observed. Apple fruit calcium levels play a vital role in fruit storage quality (Lang et al. 2001). If calcium levels in the fruit are not sufficient, physiological disorders such as bitter pit can arise during storage and transit (Lang et al. 2001). Foliar sprays are often used to increase the fruit calcium levels. However, they are costly and not very sustainable (Lang et al. 2001). Lang et al. (2001) therefore concluded that mulching improved the uptake of calcium by the tree and thus increased calcium levels in the fruit resulting in an overall decrease in bitter pit occurrence in this trial.

Living mulches may have an adverse effect on root growth and distribution due to competitive tendencies between the grass roots and the tree roots. The dense network of grass roots near the surface can limit nutrient availability to the tree roots (Haynes 1980). Tree roots are therefore encouraged downward in search of other nutrient reserves. Additionally, certain cover crops, such as clover and lucerne, are inclined to have an alleopathic effect on the tree roots, producing toxic by products of certain elements (Haynes 1980).

Different mulching materials and cover crops differ from each other regarding their contributions of nutrients and/or microbes to the soil. This is due to various factors such as, the raw materials in the mulch or the type of cover crop and the climate, as well as the soil conditions that influence the decomposition rates of the mulch or the distribution of the cover crop roots.

Soil water and availability as factors influencing root growth and development

Ground covers are known for their ability to conserve soil water and can contribute to maintaining water availability to the roots in drier seasons. Soil water consists of the soil solution, along with dissolved electrolytes, gases and water soluble compounds (Adams 1974). Water therefore provides the medium in which solutes are transported and taken up by the plant. The availability of nutrients in the soil and ultimately root growth is largely determined by soil water content (Giulivo 1990). As the performance of the orchard is closely linked to interactions between the soil water status and the tree water status, increased soil water status accompanied by increased tree water status will influence its growth rate, relating to stomatal conductance and therefore photosynthesis, and thus it's potential to acquire nutrients (Giulivo 1990).

Root growth and development in response to soil water content and availability

Soil water content and availability greatly influences root distribution and root/shoot ratios. Roots will grow and develop root clusters in areas were water accumulates in the soil, however to a point, as roots are not fond of excessively wet conditions.

Root/shoot ratios increase as a result of water deficits in the soil, provided other growth factors are not limiting (Giulivo 1990). Water uptake is maximised by root hairs, roots mining the soil for water and increased root depth (Jackson *et al* 2000; Taiz and Zeiger 2010), therefore augmenting root growth for increased surface area of functioning roots. Giulivo (1990) mentions that, when orchards are in the process of being established, rooting depth of the young trees is encouraged by a certain level of water deficit, however, that this approach would be unfavourable for established orchards. He suggests that, by reducing the root growth and thus the carbon demand of the roots by allowing for sufficient soil water, the requirement of dry matter accumulation in the canopy of established, bearing trees can be accomplished.

As with nutrient uptake, the uptake of water is dependent on the structure and conformation of the root system (Giulivo 1990). However, changes in water levels in the soil, change rooting patterns and root growth rates (Pregitzer et al. 2000). Under drought conditions, which include high temperatures and low soil water levels, root length extension is compromised (Pregitzer et al. 2000). Roots tend to grow more densely in the soil levels where sufficient water exists (Giulivo 1990). When soil water is plentiful, plants generally have shallow roots systems (Taiz and Zeiger 2010). In times of water stress, roots grow toward areas of higher water levels, which are usually deeper in the profile (Giulivo 1990). Deeper rooting is particularly important for avoiding drought risks and is beneficial in soils with low water-holding capacities (Pearson 1974). Root architecture is therefore greatly influenced by soil water levels. At the same time, uptake of water is greatly affected by root architecture (Pregitzer et al. 2000).

Irrigation methods greatly influence root distribution. Root cluster development and root length will differ under different types of irrigation, such as micro-jet sprinklers and drippers. Depending on the soil type, root length density is frequently found to be higher under drippers than under micro-jets (Searles et al. 2009). This can be attributed to the relatively small soil volume that is wetted by the dripper resulting in the necessary adaptation by the roots (Searles et al. 2009).

Roots require soil water contents to be at sufficient levels for the uptake of nutrients. The soil solution moves by diffusion or mass/bulk flow through the soil, to the root surface (Giulivo 1990; Taiz and Zeiger 2010). If water availability is limiting, nutrients are not transported to the root in sufficient quantities, and thus, nutrient uptake is compromised. Water content also affects the release of nutrients into the soil solution, making them more available for uptake (Giulivo 1990).

The influence of ground covers on water content and availability

One of the main benefits and reasons for the use of ground covers in orchards is soil water conservation. Ground covers reduce soil water evaporation from the surface (Wolstenholme et al. 1996), protecting the soil surface from direct sun rays and wind currents and thus reduce evaporative losses (Baver et al. 1972; Haynes 1980).

In this respect, living and dead ground covers differ in their effects on water content and availability. Cover crops can compete with tree crops for available water in the profile (Haynes 1980). In dry seasons this may adversely affect and restrict tree growth (Haynes 1980). Soils under clean cultivation do not experience the added risk of depleting water reserves due to the uptake of the grass cover. However, they do run the risk of the breakdown of soil structure which is in association with continued cultivation in annual crop production (Haynes 1980). This then result in increased runoff, decreased water infiltration and decreased water holding capacity (Haynes 1980). However, the use of mulching avoids both soil structure breakdown and uptake of water by another crop. Water evaporation from a mulched surface is significantly lower than that from a bare surface. Therefore water storage capacity is affected by both mulching and cover-cropping and risk of runoff is minimised with the use of mulching and cover-cropping.

Ground covers play a significant role in preserving soil physical properties which greatly influences water availability and content. In addition to reducing evaporative losses, ground covers decrease soil puddling, soil erosion and soil compaction, as well as increasing water infiltration and soil water holding capacity (Turney and Menge 1994). Water is therefore more uniformly distributed throughout the profile, both vertically and horizontally as a result of covering the surface (Lakatos et al. 2001). These factors allow for more plant available water in the soil profile which is particularly valuable in times of stress and drought (Wolstenholme et al. 1996), as well as making nutrients available to the plant in the soil solution.

In the study by St. Laurent et al. (2008) on long term orchard management systems and the resulting effect on soil microorganisms and apple replant disease, soil water content was also measured and expressed as a percentage. Soil water content was significantly higher in the mulched soil treatments (26%) as opposed to other treatments (17.4% – 19.8%). The treatments with mowed sod grass and grass maintained in the work row in between tree rows had similar soil water contents (19.8% and 18.6% respectively). Lower water contents (17.4% and 18.3% respectively) were found under treatments with annual pre- and post-emergence herbicide.

In the study by Treder et al. (2004) on the response of young apple trees to different orchard floor management systems, wood chips were applied at 20cm thickness on the surface. The three different treatments were mulching, irrigation and control with no mulch or irrigation. Soil water was higher during dry seasons in mulched plots than in control plots. Early in the season, soil water in the top 30 cm of the profile was 30% higher in mulched than the control treatments. During the season soil water levels were also significantly higher in mulched plots at 10 cm and 20 cm depths. At 30 cm depths, water levels were higher but to a lesser extent. During periods of low rainfall, soil water depletion in mulched treatments was slower than in un-mulched treatments. When irrigation stopped at the end of the season, they found that water levels in irrigation plots decreased rapidly.

With the conservation of water in the soil profile, significant savings in irrigation volumes are possible. This is extremely valuable in countries like South Africa, where water is often in short supply and requires conservation (Wolstenholme et al. 1996). Correct irrigation combined with complementary ground cover use results in reduced water stress (Neilsen et al. 2003), increased tree vigour and increased fruit yield (Szewczuk and Gudarowska 2004).

Soil air and aeration as factors influencing root growth and development

The soil atmosphere comprises oxygen and carbon dioxide, amongst others. Oxygen is required by the roots and other living organisms for life, and is supplied by the soil atmosphere (Stolzy 1974). The soil acts as an oxygen sink to the above ground atmosphere which has an unlimited supply of oxygen. Carbon dioxide is formed by respiring cells and is released into the soil (Stolzy 1974). The plant therefore produces carbon dioxide and uses oxygen in the soil, which acts both as a source and a sink for these life giving gases (Stolzy 1974). Ground covers can increase the porosity of the soil and therefore improve soil aeration.

Root growth and development in response to soil air and aeration

Sufficient soil aeration is vital for a healthy, functioning root system. Due to the lack of drainage in the soil, surplus water in the profile along with soil compaction are often causes of poor soil aeration (Stolzy 1974; Taiz and Zeiger 2010). Factors that cause poorly aerated soils have unfavourable effects on root size and depth, as oxygen availability becomes limiting to the growing and dividing cells (Stolzy 1974; Taiz and Zeiger 2010). Reduced mineral uptake by the roots is another response of poor aeration in the soil (Stolzy 1974).

Roots require oxygen from the soil for aerobic respiration (Taiz and Zeiger 2010). Oxygen is obtained from the gas-filled pore spaces in the soil and reaches depths of several meters in the soil due to diffusion through the pore spaces (Taiz and Zeiger, 2010). Concentrations do however decrease down the profile. When flooding or compaction occurs, these pore spaces are filled or closed and reduce the availability of oxygen to the roots (Taiz and Zeiger 2010). Lack of oxygen is not the only factor of anaerobic conditions to adversely affect plants. A series of reduction reactions such as denitrification, manganese reduction, iron reduction and sulphate reduction can occur (Hillel 1980). Several of the products of these reactions are toxic to plants such as ferrous sulphide, ethylene, acetic butyric and phenolic acid (Hillel 1980).

Anoxic (absent soil oxygen) and hypoxic (abnormally low soil oxygen) conditions in soils can reduce root elongation, severely damage roots and result in decreased yield. This is due to the inhibition of cellular respiration of the root cells (Taiz and Zeiger 2010). Different plant species have different levels of sensitivity to hypoxic and anoxic soils. Some plants are adversely affected by anoxic soils in under 24 hours, whilst others can tolerate anoxic soils for a few days before root damage occurs (Taiz and Zeiger 2010). Root distribution is largely determined by oxygen levels down the profile and thus the majority of roots occur higher up in the profile where oxygen is more available.

According to Stolzy (1974), Boynton and Reuther (1939) and Compton and Boynton (1944) spring is a critical time in orchards for sufficient oxygen availability. Root flushes occur in spring and it is very important that oxygen is not limiting at this time. During dormancy and low temperatures, oxygen depletion is slow and does not have a significant effect on the root system (Taiz and Zeiger 2010). However, with higher temperatures during the growing season, oxygen is rapidly depleted from the soil and can have detrimental impacts on the root system and the plant (Taiz and Zeiger 2010). Taiz and Zeiger (2010) also report that, under these conditions, oxygen levels can become critically depleted within 24 hours as a result of the consumption by roots, soil fauna and microorganisms.

Low oxygen levels in the soil can furthermore lead to diseases of the roots such as root rot. Avocados are particularly at risk of contracting root rot caused by *Phytophthora cinnamomi* in conditions of low oxygen content in the soil (Stolzy 1974).

Oxygen depleted soils (anaerobic conditions) are more limiting to plants than soils with excess carbon dioxide (Stolzy 1974). Carbon dioxide levels in the soil can however have an effect on root growth. Excessive concentrations of carbon dioxide in the soil can diminish oxygen levels slightly, but the high concentration of carbon dioxide required for this will affect the plant more seriously than the lack of oxygen (Hillel 1980). High levels of carbon dioxide have been shown to limit metabolic activities of plants and decrease root mass while increasing shoot growth (Woolley 1965 according to Stolzy 1974). However, certain levels of carbon dioxide have also been shown to stimulate root growth (Stolzy 1974).

The influence of ground covers on soil air and aeration

Ground covers influence soil physical properties, improving soil porosity and encouraging efficient and healthy root growth. Soil aeration is limited when gas-filled pore spaces are reduced due to flooding or compaction (Stolzy 1974; Taiz and Zeiger 2010). Organic ground covers increase the organic matter content of the soil, therefore increasing soil aeration, making the soil more habitable to roots and microorganisms (Haynes 1980).

In the study by St. Laurent et al. (2008), organic matter in the soil was the highest under mulched treatments and grass lanes, resulting in soil aeration also being highest in these plots.

Limited aeration by compaction may restrict microbial activity (Baeumer and Bakermans (1973) ref. by Haynes 1980). However Domsch (1977), ref. by Haynes (1980), suggests that tree roots are more sensitive to limited oxygen levels due to reduced gas diffusion in compacted soils than microorganisms are, as the oxygen demand by microorganisms is often satisfied in soils with reduced gas-filled pore spaces.

Carbon dioxide levels in the soil are altered by respiring cells and microorganisms. Pregitzer et al. (2000) points out that respiration increases with increasing soil temperatures. Ground covers are responsible for keeping the soil warmer in times of low temperatures, thus increasing respiration rates in times when respiration is low. Carbon dioxide levels are therefore increased in these times, influencing the soil's air composition. Maintaining good aeration and increasing organic matter in the soil is therefore very important for improving the soil environment for roots and microorganisms (Haynes 1980).

Mycorrhizal population as a factor influencing root growth and development

Mycorrhizae increase the efficiency of nutrient uptake in the soil. Roots therefore have access to more nutrients than they otherwise would, allowing for increased nutrient uptake and increased root growth. Different types of ground covers influence mycorrhizae colonisation of the roots. Some materials influence colonisation positively, and others negatively.

Root growth and development in response to mycorrhizal population

Mycorrhizae are fungi that populate the roots of most plants. Roots and mycorrhizae generally have a symbiotic relationship where the fungi assists the roots in the uptake of nutrients, while the roots act as hosts, providing food in the form of carbohydrates to the fungi (Gerdemann 1974). With the colonisation of mycorrhizae comes a change in the morphology of the roots (Gerdemann 1974), however this colonisation of the fungi is not pathological, provided a balanced relationship remains (Gerdemann 1974).

There are two major classes of mycorrhizae: ectotrophic mycorrhiza and arbuscular mycorrhizae (Taiz and Zeiger 2010). Ectotrophic mycorrhizae form a thick sheath of mycelium around the roots called the mantle, whereas arbuscular mycorrhizae form a less dense arrangement of hyphae around and within the root (Taiz and Zeiger 2010). The most commonly occurring mycorrhizae that colonise the roots of apple trees are arbuscular mycorrhizae (Derkowska 2008). They play a very important role in protecting the tree from adverse conditions such as salinity, acidification and drought (Derkowska et al. 2008).

Mycorrhizae consist of hyphae and fine tubular filaments, the mass of which form the bodies of the fungi, the mycelium (Taiz and Zeiger 2010). Due to their fine nature, the hyphae are able to extend further than the root itself and maximise nutrient acquisition (Taiz and Zeiger 2010). This facilitates the uptake of minerals, particularly those that are relatively immobile in the soil, such as phosphorous (Taiz and Zeiger 2010). The soil-root interface is extremely important for the uptake of nutrients and contact must be maintained. The hyphae are therefore able to enhance the effective contact the root has with the soil, increasing the soil-root interface (Giulivo 1990). Mycorrhizae also facilitate the uptake of water. They are able to change the movement of water entering or exiting the plant, as well as alter water movement in the plant (Taiz and Zeiger 2010).

Mycorrhizae populations can be suppressed in certain conditions such as dry or water logged soils, or saline conditions. In addition, the absence of mycorrhizae can also be due to extreme soil fertilities, being either too high or too low (Taiz and Zeiger 2010).

The fungi-host relationship can become a pathological association (Taiz and Zeiger 2010). This occurs if the soil is of sufficient fertility but the fungi still relies on the host plant for carbohydrates (Taiz and Zeiger 2010), even though the plant no longer requires assistance from the fungi for the uptake of nutrients. Host plants can suppress mycorrhizae in situations such as these. Thus, slight deficiencies of nutrients, particularly phosphorous, can encourage mycorrhizal fungi (Taiz and Zeiger 2010). The uptake of phosphorous is increased by the mycorrhizal colonisation of apple roots in phosphorous depleted soils; whereas in soils where phosphorous is abundant, mycorrhzal colonisation increases the efficiency of copper and zinc uptake by the roots (Derkowska et al. 2008). Lakatos et al. (2001) conducted a study on the effects of ground management systems on the number of soil micro organisms and tree nutrition in apple trees. Results showed that increased mycorrhizal colonisation resulted in increased levels of copper and zinc in the leaves. According to Derkowska et al. (2008), in phosphorous abundant soils, mycorrhizae increase the efficiency of copper and zinc uptake by the roots.

The influence of ground covers on the mycorrhizal population

Mycorrhizal colonisation is increased with greater root surface area and the growth of fine feeder roots (Derkowska et al. 2008). The use of ground covers enhances root growth and development by altering and improving other factors responsible for root growth. However, the type of ground cover plays a significant role in the extent of mycorrhizal colonisation of the roots and some ground cover material can influence colonisation adversely.

Derkowska et al. (2008) showed the influence of mycorrhization and organic mulching on the extent of mycorrhizal colonisation (mycorrhizal frequency) in apple and strawberry roots. They compared treatments where various mulches were applied, to treatments where mycorrhizal inoculation was applied. The treatments were follows: (1) Control (un-mulched and not inoculated); (2) Deacidified peat (pH 6.5); (3) Hard wood bark mulch; (4) Sawdust mulch; (5) Horse manure mulch; (6) Plant compost mulch; (7) Mycorrhizal substrate containing five *Glomus* species; and (8) Straw mulch. From their results it is evident that more mycorrhizal colonization occurred on the strawberry roots than it did on the apple roots. This is due to greater size of the strawberry root system as well as the higher density of fine feeder roots and root hairs. With regard to the strawberry roots, the highest mycorrhizal frequency (87.78%) was found to be in the mycorrhizal substrate treated plots and the control plots, and the lowest frequency (35.55% and 32.22% respectively) were found in the peat and sawdust mulched plots. The other treatments were observed to have mycorrhizal colonisation to an intermediate extent. The apple roots, however, demonstrated different trends. The highest mycorrhizal frequency (25.83%) was found in the peat and bark mulched plots (higher than the mycorrhizal treated plots), and the lowest frequency (3.33%) was found in the sawdust and manure mulched plots. The other treatments were intermediately colonized by mycorrhizae. It is therefore evident that mycorrhial frequency is influenced by the type of ground cover material used, as well as the type of roots that it is colonizing. Derkowska et al. (2008) mentions that the extent of colonisation is dependent on age of the roots and environmental conditions and may change from year to year, as well as colonisation may be delayed as a result of environmental conditions.

In the study conducted by Lakatos et al. (2001) on the effects of ground management systems on the number of soil microorganisms and tree nutrition in apple trees, mycorrhizae colonisation rate was also measured. Treatments were as follows: (1) Straw; (2) Livestock manure; (3) Black plastic foil; (4) Pine bark mulch; and (5) Clean cultivation. Clean cultivation had the highest colonization rate (62%), followed by plastic foil (58%) and pine bark mulch (57%). The lowest colonization rate was found in the livestock manure treatment (9%). Livestock manure and straw mulches particularly had negative effects on the infection rate. This is due to the increase in soil nitrate, P_2O_5 and K_2O which has an adverse effect on the mycorrhizal colonization of the roots.

Conclusion

Factors in the root environment such as soil physical properties, soil temperature, soil nutrient and -organic matter content and availability, soil water content and availability, soil air and aeration, and mycorrhizae colonisation of the roots, can greatly alter and improve root growth and development. These factors are often linked in their ability to change the root environment, and this must be considered as a whole when studying them and drawing conclusions on their effect. An enhanced root environment results in a healthy, more efficient root system, and roots are able to make efficient use of resources, preventing the necessity for excessive applications of inputs such as fertilizers and irrigation. In this case resources are not easily wasted as the roots are functioning and growing at an optimum. Efficient root systems ultimately encourage increased yield and quality of fruit.

There are various different soil management techniques applied in orchards systems to improve soil physical properties, temperatures, nutrient and organic matter availability, water availability, air and aeration and mycorrhizal colonization. The correct use of ground covers (living or dead) has been found to be beneficial with regards to positive changes to the soil and root environment. Conservation of the soil and its properties is extremely important for agriculture and the future thereof. With the conservation of good quality soils and the improvement of poorer quality soils, root growth and development of crop plants can be enhanced, thus influencing overall productivity of cropping systems. Cost, maintenance and availability may limit the use of ground covers and advantages and disadvantages must be weighed up against each other for each proposed crop. As a result, root growth and development can be enhanced with the use of this non-invasive ground management system, resulting in improved yield and quality via more efficient uptake of nutrients and water.

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Paper 1

Quantifying the changes in soil physics, temperature and water in the root environment of 'Cripps' Pink' apple trees after application of different mulches.

Introduction

In order to achieve good fruit production and quality, factors of the growth medium that determine root growth and development must be optimal. The soil environment is capable of offering a good habitat for root growth as it can provide the necessary environmental factors important for root growth and development, however, it can hamper growth if conditions are not conducive (Giulivo 1990). The use of mulching in orchards can provide producers with a sustainable tool to improve soil conditions.

Soil physics encompasses properties such as bulk density, porosity, texture, pedality, soil pressure and soil resistance, all of which make up the soil fabric (Taylor 1974; Hillel 1980). These properties, amongst others, have a great influence on soil water and soil temperature (Taylor 1974; Hillel 1980). These properties therefore contribute significantly to the behaviour of growing roots and developing root systems (Taylor 1974). Maintaining the structural stability of the soil is therefore of great importance and can be successfully done by the use of mulches as they provide a protective covering to an otherwise vulnerable soil surface (Haynes 1980).

Bulk density affects the penetrability of the roots through the soil and is determined by the extent of soil compaction and clay and organic matter content (Hillel 1980). Hillel (1980) reported that the bulk density of soils can range between 1.6 kg/ℓ in sandy soils and 1.1 kg/ℓ in loams and clay soils. Bulk density can be decreased by increasing the organic matter via mulching. Covering the soil surface with a mulch can improve the soil's bulk density and thus create a more favourable environment for root penetration and growth. Organic mulches are better known for this quality due to the addition of organic matter to the soil though decomposition and incorporation.

Soil resistance, otherwise known as electrical resistance of a soil (Hillel 1980), is determined by various factors that also influence root growth and development. These factors include water content, soil composition, texture and the concentration of soluble salts. Soil wetness can be evaluated by the soil's resistance (Hillel 1980), where a decrease in soil resistance is often accompanied by an increase in soil water. As ground covers are known to influence these factors, it is likely that the application of mulches will influence soil resistance.

Due to the sensitive behaviour roots show to temperatures and temperature fluctuations, ameliorating the soil's temperature and effects thereof is of great importance in creating a favourable environment for root growth (Janick 1986; Pregitzer et al. 2000). Fluctuating temperatures are considerable on and near the soil surface, particularly uncovered soils (Pregitzer et al. 2000), but these fluctuations tend to decrease with profile depth. The insulating, shading and heat absorbing properties of ground covers can assist in buffering temperature fluctuations and achieve a favourable root environment (Janick 1986). This is partly attributed to the improvement of the water status in covered soils, which results in a more mesic soil environment (Lanini et al. 1988).

Soil water status and tree water status are closely linked to the performance of a fruit orchard (Giulivo 1990). An increase in soil water status is accompanied by an increase in tree water status up to a point, at which water logged conditions reduce water uptake. As a result of this association, the tree's growth rate is influenced, resulting in a change in the tree's potential to acquire nutrients (Giulivo 1990). Mulches are known for their ability to increase soil water by decreasing evaporative losses (Baver et al. 1972; Haynes 1980; Wolstenholme et al. 1996). In addition to reducing evaporative losses, mulches preserve the physical nature of soils by decreasing soil puddling, soil erosion and soil compaction, as well as increasing water infiltration and soil water holding capacity (Turney and Menge 1994). As result, water is more uniformly distributed through the profile (Lakatos et al. 2001) and the plant available water in the soil profile is increased (Wolstenholme et al. 1996).

This study was proposed due to the lack of sufficient, reliable information on the short term effects of mulches on the root environment of apple orchards. It is hypothesised that an increase in organic matter in the soil with organic mulches will improve the soil's physical properties through a decrease in bulk density and an increase in resistance with regard to salinity over time. It is also hypothesised that temperature fluctuations will be buffered by a mulch, particularly in times of suboptimal temperatures, creating more optimal temperatures for root growth for greater parts of the season. With the soil temperature buffering properties, as well as the soil water conservation properties of a mulch, soil water levels are expected to be higher in mulched soils, as opposed to un-mulched soils. The impact on soil water levels is expected to be more noticeable in the organic mulches which contribute to the organic matter content of the soil, which in turn increases the water holding capacity of the soil.

Materials and Methods

Trial Layout

The trail was carried out at Lourensford Estate, Somerset West, South Africa (-34° 2' 31.29", +18° 55' 16.20") and commenced in October 2008 (Kotze et al. 2012). The trial consisted of two 'Cripps' Pink' apple orchards planted in 1998 on M793 rootstocks on two different soil types. One site was on a heavier soil (Clovelly) and the other, an adjacent orchard, on a lighter soil (Tukulu) (Table 1).

The trial layout was a randomized complete block design with 5 treatments, 6 blocks, repeated on the 2 sites. Two buffer trees were added between plots to differentiate clearly between each plot. Each plot comprised four trees.

Of the five treatments, three were mulches consisting of organic materials, one of an inorganic material and the remaining one was the control, with no mulch. The organic mulches were as follows: wood chips containing no initial significant nutrient levels and originating from various tree species (excluding pine as it is known to leach allelochemicals); compost, where the nutrient levels were determined and vermi-castings (also with determined nutrient composition) with wood chips placed on top to prevent loss of the castings due to rain or wind. The inorganic mulch was a black polytex PT110 woven geotextile fabric that allowed water and nutrients to penetrate the soil, but contained no nutrient levels itself. The control treatment was not mulched and was under clean cultivation, where weeds were controlled according to farm management.

Normal commercial practises were followed regarding orchard management, apart from the irrigation. In January 2011 every second 42 ℓ h^{-1} micro-jet was replaced with a 20 ℓ h^{-1} micro-jet, reducing the deliverance of water due to suspected over irrigation, which became evident from historical data (Kotze et al. 2012). In October 2011 it was decided to further reduce irrigation, based on data acquired from FruitLook satellites, which was only available from 2011 and illustrated a lack of evapotranspiration deficit in both sites (fruitlook.co.za) (Fig. 1), and thus the deliverance was further reduced by replacing every 42 ℓ h^{-1} micro-jet in the trial with 20 ℓ h^{-1} micro-jet. Evapotranspiration deficit is a measure of plant water stress.

Although under normal crop production condition, plant water stress is not usually favourable, due to the nature of the trial and the use of mulching which essentially is a water conservation tool, a certain amount of water stress was require in order to receive results with regard to the mulches. The change in irrigation volumes, however, did not result in water reductions to the extent that would inflict stress on the control plots. The only spikes in evapotranspiration deficit were noted in times of heat waves where ambient temperatures reached upper thirties. The irrigation scheduling was maintained by the farm manager at two hours, three times per week, however irregularities in the irrigation scheduling were found during visits to the sites on various occasions.

Application of Mulches

Organic mulches were reapplied every year from trial commencement in October (2009 – 2011) to maintain a thickness of approximately 5cm on the soil surface. The inorganic mulch treatment, black polytex PT110 woven geotextile fabric, remained from the commencement of the trial.

A total of 90 ℓ of compost and woodchips respectively were evenly dispersed over their respective treatments per block during each reapplication. A total of 60 ℓ of vermi-castings, topped with 30 ℓ of woodchips, were evenly dispersed per block for the vermi-castings treatment.

Soil Physical Analysis

In May 2012 a soil physical analysis was performed in order to compare the mulched treatments with the control treatment. Six replicate samples per plot were taken per site from each treatment. Two subsamples were taken to make a composite sample from each plot at 0 -10 cm, 10 – 30 cm and 30 – 50 cm depths. The bulk density and resistance and stone fraction of the soils were analyzed.

All sampling was done using a 5 cm Thomson’s auger and were analyzed by a commercial laboratory (BemLab Pty Ltd, Strand, South Africa).

Soil Water and Temperature

Water in the soil is referred to as soil water in this paper and refers to the water fraction in the soil that is available for uptake.

Soil water and temperature were measured on a continuous hourly logging basis by DFM probes (DMF, Continuous logging Soil Moister Probe, DFM Software Solutions CC, South Africa). DFM probes were installed in September 2010 and due to financial constraints, they were installed in only one plot per site (Kotze et al. 2012).

Relative soil water (% DFM soil water content) was measured at every 10 cm by sensors in the probes that reached down to 60 cm. Calibrative line graphs were required in order to convert the DFM soil water readings into quantitative soil water content (volumetric soil water content). This was done by taking four sets of soil samples at different soil water levels, providing a great enough soil water range to make an accurate calibration with the corresponding DFM soil water readings. Sampling was therefore done during ‘wet’ and ‘dry’ cycles, when the soil was either just irrigated or after significant water depletion. Samples were taken with a 5 cm Thomson’s auger. Sampling was done as close to the DFM probes as possible, without impacting DFM measurements (approximately 5 cm away from the probe), at 10 cm, 20 cm, 30 cm and 40 cm. Gravimetric soil water content was calculated (soil water in terms of mass represented by weight; product of mass and the gravitational acceleration), and then converted to volumetric soil water content (soil water in terms of volume). The samples were weighed in the laboratory to determine their total weight (A) and then oven dried for approximately twenty four hours at 105°C. They were then weighed again to determine the weight of solids (B). Gravimetric water content (w) was calculated according to Equation 1.

$$w\ (\%) = \frac{A-B}{B} \times 100 \qquad (1)$$

Gravimetric water content was converted to volumetric water content with the use of estimated, set bulk density (ρ_b) values (ρ_b = 1.4 for the heavier soil; ρ_b = 1.5 for the lighter soil). The volumetric water content (θ) was calculated according to Equation 2.

$$\theta\ (\%) = w \times \rho_b \qquad (2)$$

Statistical Analysis

All data that was of a statistical nature was analyzed using the Statistical Analysing System (SAS) programme 9.1 (SAS Institute Inc, 2004, Cary, NC). Analyses of variances were analyzed using a General Linear Model (GLM) procedure and standard errors and least square means were calculated for each treatment. Data was considered significant at a 5% significance level and 10% significance level where specified.

Results

Soil Physical Analysis

0 – 10 cm

In the heavier soil site, there were no significant differences between treatments in the physical analysis at the 0 – 10 cm layer of the soil profile, except for the soil resistance analysis (Table 2). The geotextile fabric treatment had the highest soil resistance, but only differed significantly (P = 0.0013) from the compost and vermi-castings treatments. The vermi-castings treatment had the lowest soil resistance.

In the lighter soil site, there were no significant differences between treatments in the physical analysis at the 0 – 10 cm layer in the soil profile (Table 3).

10 – 30 cm

The physical analysis in the heavier soil site at the 10 – 30 cm layer of the soil profile showed significant differences between treatments in the bulk density analysis (P = 0.0558), percentage silt of the soil (P = 0.0855) and the resistance of the soil (P = 0.0001) (Table 4). The control treatment had the highest bulk density and differed significantly from the vermi-castings and the woodchips treatments. The bulk density of the geotextile fabric treatment was just lower than the control treatment and differed significantly from the woodchips treatment. The compost treatment did not differ significantly from any of the other treatments.

In the lighter soil site, similar results were found at 10 – 30 cm as in the top 10 cm, as there were no significant differences between treatments (Table 5).

30 – 50 cm

In the heavier soil site, similarly to the 0 – 10 cm soil layer, there were no significant differences between treatments in the physical analysis at the 30 – 50 cm layer of the soil profile, except for the soil resistance analysis (Table 6). The control treatment, followed by the geotextile fabric treatment had the highest soil resistance and differed significantly (P =

0.0179) from the compost and vermi-castings treatments. Following the geotextile fabric treatment was the woodchips treatment, which did not differ significantly from any of the other treatments. The vermi-castings treatment had the lowest soil resistance.

No significant differences between treatments were found in the physical analysis in the lighter soil site at the 30 – 50 cm layer in the soil profile (Table 7).

Soil Temperature

Historical soil temperature data from 2010, adapted from Kotze et al. (2012), was used along with data measured during 2011 and 2012.

In the heavier soil site, the woodchips treatment consistently had the highest average summer and winter temperatures over the two seasons in the top 10 cm layer of the soil profile (Fig. 2). The compost and vermi-castings treatments closely followed the woodchips trend, at times surpassing woodchips temperatures particularity in January and February. The organic mulches therefore showed consistently warmer, average temperatures throughout the two seasons, at times reaching approximately 2°C higher than the other treatments. The geotextile fabric treatment showed consistently cooler average temperatures over the two seasons, particularly in the winter months. This trend was closely followed by the control treatment, at times experiencing lower soil temperatures than the geotextile fabric mulch. The control treatment did, however, experience higher average temperatures, predominantly in the summer months, at times, identical organic mulch temperatures. The control treatment therefore showed more fluctuating tendencies with regards to its average temperatures over the two seasons. The control and the geotextile fabric treatments also showed quicker cooling during the autumn months, creating a greater difference in average temperature between them and the organic mulch treatments.

Similar trends to that of the 10 cm soil layer were shown in the 20 cm, 30 cm and 40 cm layers of the heavier soil site, however, daily temperatures fluctuated less down the profile by approximately 4°C difference from the 10 cm layer to the 40 cm layer (Fig. 3, 4 and 5). The control treatment also reached lower temperatures more often at the 20 cm and 40 cm layers, particularly in the spring-to-mid-summer months. The geotextile fabric treatment had consistently the lowest average temperature at all of the depths, where as the woodchips treatment had consistently the highest average temperature at all of the depths.

More of a variation in average temperatures between treatments, and higher average temperatures were observed in the lighter soil site as compared to the heavier soil site. The buffering characteristics of mulches, particularly the organic mulches, were also more prominent in the lighter soil site. In the 10 cm soil layer of the lighter soil site, the control treatment frequently had the highest average summer temperatures and the lowest average winter temperatures, sometimes differing by up to 3°C, compared to the organic mulches (Fig. 6). It was closely followed, if not occasionally surpassed, by the geotextile fabric treatment. The organic mulch treatments, lead by the woodchips treatment, had the highest average winter temperatures. Highest average temperatures alternated between the organic mulches and the control treatment during the summer months.

Similar trends to that of the 10 cm soil layer were shown in the 20 cm, 30 cm and 40 cm layers of the lighter soil site, however, daily temperatures over all of the treatments fluctuated less down the profile by approximately 4°C difference from the 10 cm layer to the 40 cm layer (Fig. 7, 8 and 9). In the 40 cm soil layer the woodchips treatment was rarely surpassed by the control treatment with regards to average highest temperatures (Fig. 9). The woodchips treatment therefore kept the soil warmer to greater depths compared to the other treatments. The vermi-castings treatment also reached lower average temperatures more frequently at this depth, particularly during the cooler months.

Maximum and minimum daily temperatures in the top 10 cm layer of the profile for the summer months (01 September 2011 – 29 February 2012) are displayed in Fig. 10 and 11 for the heavier soil site and in Fig. 12 and 13 for the lighter soil site. This period includes some of the critical growth and development stages of the trees, including full bloom (October), one of the root growth flushes (November – January) and times of potential water and temperature stress (January – February) for apple trees.

In the heavier soil site the treatments all followed a similar trend for the month of September with regards to the maximum daily temperatures (Fig. 10). From October the control and geotextile fabric treatments began to deviate from the other treatment and alternated with each other for the highest maximum temperature until the end of February. In addition to frequently having the highest maximum soil temperature, the geotextile fabric treatment also had the lowest maximum temperatures at times. The organic mulches all followed similar trends throughout the growth season, with the vermi-castings treatment sometimes having the lowest maximum temperature, particularly during the month of January. The compost treatment did, however, deviate slightly from the other two organic treatments from December, and began to follow a similar trend to the control treatment.

As with the maximum temperatures, the organic mulches show similar trends to each other with regards to the minimum daily temperatures in the heavier soil site (Fig. 11). The woodchips and compost treatments alternated with each other for the highest minimum daily temperatures, followed closely by the vermi-castings treatment. The geotextile fabric treatment consistently had the lowest minimum temperature, followed by the control treatment. These two treatments therefore showed the greatest fluctuations, frequently having the highest maximum and lowest minimum temperatures. The organic mulches, particularly the woodchips treatment, showed the least variation in daily maximum and minimum temperatures in the top 10 cm of the soil. The organic mulches were therefore effective in buffering the soil against temperatures extremes. This is supported by the finding that at times maximum daily temperature of the geotextile fabric treatment was up to 3°C warmer than the woodchips maximum daily temperature and up to 2°C cooler than the woodchips minimum daily temperature.

At the lighter soil site the control treatment deviated dramatically from the other treatments with regards to the maximum daily temperatures from September to mid December, reaching maximums of up to 9°C warmer than the other treatments (Fig. 12). From mid December to the end of February the woodchips treatment experienced the highest maximum daily temperatures, however, these maximum temperatures were not as high as those experienced in the control treatment earlier in the season. During this period the control treatment followed similar trends to the other treatments, sometimes experiencing the lowest maximum temperatures. The vermi-castings treatment consistently had the lowest maximum temperature throughout the season, on occasions being surpassed by the geotextile fabric and control treatments. In contrast to the heavier soil site, the geotextile fabric treatment did not experience the same extremes in maximum temperatures as the other treatments.

During the first part of the season the control treatment had significantly lower minimum temperatures in the lighter soil, reaching temperatures up to 2°C lower than the other treatments, making it the treatment experiencing the greatest temperature fluctuations at this time (Fig. 13). It continued to have the lowest minimum daily temperatures for the rest of the season, but to a lesser extent and was closely followed by the geotextile fabric treatment. The organic mulches followed similar trends throughout the season, with the vermi-castings treatment consistently having the highest minimum temperature. The vermi-castings treatment therefore fluctuated the least of all of the treatments in the lighter soil site, having the highest minimum temperature and the lowest maximum temperature.

An analysis of the hourly temperatures during the first week of January in the top 10 cm of the heavier soil indicated that the temperature in the geotextile fabric treatment followed by the control treatment fluctuated the most on a diurnal basis, varying by approximately 4-7°C (Fig. 14). It is also evident that the geotextile fabric treatment warmed up quicker than the other treatments during the day, peaking up to 6 hours before other treatments. The woodchip treatment fluctuated the least of all the treatments, with temperatures within an approximate 2-3°C range on a diurnal basis. The vermi-castings and compost treatments followed a similar trend to the woodchips treatment, however the vermi-castings treatment remained consistently cooler and the compost treatment remained consistently warmer than the woodchips treatment.

In contrast to the heavier soil, the hourly temperatures during the first week of January in the lighter soil site indicate that woodchips treatment remained consistently warmer than the other treatments by approximately 2°C (Fig. 15). The woodchips treatment also fluctuated approximately 5°C on a diurnal basis. The geotextile fabric and control treatments also fluctuated approximately 5°C on a daily basis, with the control treatment remaining consistently cooler than the other treatments. The vermi-castings treatment, followed by the compost treatment, appeared to have the most sTable hourly temperatures.

Soil Water

Historical soil water data from 2010, adapted from Kotze et al. (2012), as well as soil water data measured during 2011 and 2012 is presented. All water data presented in this paper was converted into volumetric water content. Due to only one replicate of the DFM probes in only one plot per site, data is not statistical.

It is evident that the reduction in irrigation deliverance in January and October 2011, discussed earlier, was fairly successful in reducing soil water content by approximately 10% in the heavier soil site (Fig. 16 – 19) and approximately 5% in the lighter soil site (Fig. 20 – 23).

In the heavier soil site, the geotextile fabric treatment consistently had the highest average water content over the two seasons in the top 10 cm layer of the soil profile, fluctuating around 50% in 2010 and 45 – 50% in 2011 and 2012 (Fig. 16). Soil water in the compost treatment followed the trend of the geotextile fabric closely, and at times even surpassing it. The woodchips treatment, however, consistently had the lowest average water content over the two seasons, which at times was over 20% lower than that of the geotextile fabric treatment, and fluctuating around 43% in 2010 and 30 – 35% in 2011 and 2012. The vermi-castings and control treatments remained relatively intermediate to the other treatments in terms of soil water content. The sudden drops of a single treatment at times throughout the measurement period were attributed to blocked sprinklers which were noted and repaired or replaced during site visits. The decline in soil water content experienced in all treatments at the same time is attributed to a reduction in irrigation, or rain during the winter months. It is also evident that the soil water content in the control treatment fluctuated more than the other treatments.

Trends changed considerably from the 10 cm soil layer to the 20 cm layer of the heavier soil site as the compost treatment surpassed the woodchips treatment with the lowest average water content, and consistently remained approximately 10% lower than the other treatments over the two seasons (Fig. 17). The vermi-castings treatment realised average soil water contents of approximately 5% higher than the other treatments in 2010, but was similar to the other treatments in 2011, which all followed similar trends and soil water levels over the two seasons. The control treatment continued to fluctuate at this depth.

In the 30 cm soil layer of the heavier soil site, greater differences in average soil water levels between treatments were noted (Fig. 18). The control and vermi-casting treatment followed a similar trend and had consistently higher soil water levels over the two seasons compared to the other treatments at this layer. As in the 20 cm layer, the compost treatment had consistently lower average soil water contents. The woodchips and geotextile fabric treatments remained relatively intermediate to the other treatments.

In the 40 cm soil layer of the heavier soil site the vermi-castings treatment, followed by the geotextile fabric woodchips treatments had consistently higher average soil water contents over the two seasons (Fig. 19). The compost treatment continued to exhibit the lowest average soil water level, and it was followed by the control treatment.

In the lighter soil site, the compost treatment consistently had the highest average soil water content over the two seasons in the top 10 cm layer of the soil profile, fluctuating between 30 – 35% in 2010 and 25 – 40% in 2011 and 2012 (Fig. 20). In 2010 the vermi-castings and woodchips treatments followed a similar trend to that of the vermi-castings treatment. In 2011, however, the compost treatment deviated somewhat from the other treatments with increasing average soil water contents, reaching levels approximately 10% higher than the other treatments. In 2010 the geotextile fabric treatment exhibited the lowest average soil water content, and was followed by the control treatment. In 2011 and 2012, all the treatments exhibited similar water contents, except for the compost treatment until the beginning of 2012, and all followed similar trends over the season.

In the 20 cm soil layer of the lighter soil site, all of the treatments, with the exceptions of the woodchips treatment, had similar average soil water contents and generally ranged between 20 and 25% (Fig. 21). The geotextile fabric treatment frequently had the highest average soil water content and the control and vermi-castings the lowest of these treatments. The woodchips treatment, however, exhibited consistently lower average soil water contents over the two seasons, which were generally 10% lower than the other treatments.

In the 30 cm soil layer of the lighter soil the treatments all followed relatively similar trends to that of the 20 cm layer, however, treatments deviated more from each other (Fig. 22). The geotextile fabric treatment consistently exhibited the highest average soil water level, followed by the compost, vermi-castings and control treatments. The woodchips treatment consistently displayed the lowest average soil water levels, only being surpassed by the control treatment at the beginning of the season in 2010.

Similar trends to that of the 30 cm soil layer were found in the 40 cm layers of the lighter soil site (Fig. 23).

The average daily soil water contents for the 2011/2012 season (1September 2011 – 29 February 2012) of the 10 cm and 40 cm soil layers are present as noTable changes occurred between these depths (Fig. 24 – 27). As mentioned earlier with regards to the soil temperatures, this period encompasses critical growth and development stages of the trees.

In the 10 cm soil layer of the heavier soil site, the water content of the geotextile fabric, compost, control and vermi-castings treatments all followed similar trends and generally ranged between 40% and 50% (Fig. 24). The highest average daily soil water content was found in the geotextile fabric and compost treatments which alternated with each other. The woodchips treatment, however, exhibited the lowest average daily soil water content throughout the season, which generally ranged between 30% and 40 %. It is evident that irrigation was reduced towards the end of September and the decrease in soil water content found at the end of January and the beginning of February in the vermi-castings and compost treatment can be attributed to blocked sprinklers, as daily irrigation spikes were not apparent during this time in these treatments as compared to the control treatment.

In the 40 cm soil layer of the heavier soil site, the average daily soil water contents of the treatments deviated more from each other than in the 10 cm soil layer (Fig. 25). The vermi-castings treatment, followed by the geotextile fabric treatment, exhibited the highest average daily soil water contents. In contrast to the 10 cm soil layer, the compost treatment had the lowest average daily soil water content. The vermi-castings treatment had a 20% higher soil water contents compared to the compost treatment. The control treatment followed the compost treatment with the lowest average daily soil water contents. The woodchips treatment remained intermediate to the other treatments in this regard. The overall average daily soil water contents fluctuated less in the 40 cm soil layer compared to that of the 10 cm layer. The lowest variation in daily soil water content was observed in the compost treatment.

In the 10 cm soil layer of the lighter soil site, the compost treatment achieved the highest average daily soil water contents during the season, ranging between 30% and 35%, until January, at which time it decreased and was not different to the other treatments (Fig. 26). The other treatments all followed similar trends at similar soil water contents, ranging between 20% and 30%, and dropping to approximately 15% in January. The woodchips, geotextile fabric and vermi-castings treatments alternated with regards to realising the lowest average daily soil water content.

As in the heavier soil site, the 40 cm soil layer of the lighter soil site experienced less deviation in the average daily soil water contents in the 40 cm soil layer, compared to that of the 10 cm soil layer (Fig. 27). The geotextile fabric treatment, followed by the compost, control and vermi-castings treatments, exhibited the highest average daily soil water content during the season. The soil water content of the geotextile fabric treatment also remained relatively constant during the season (approximately 23%), whereas the other treatments experienced a decrease in January. The greatest decrease was found in the compost and woodchips treatments. The woodchips treatment resulted in the lowest average daily soil water content throughout the season (approximately 16% September – December; approximately 13% January – February).

Discussion

Soil Physical Analysis

Significant differences between treatments with regard to soil resistance were found in the heavier soil site at all three of the soil layers analysed. The same trend was observed in the three soil layers, however, only differing slightly in the 30 – 50 cm layer. The control, geotextile and woodchips treatment had the highest resistances, with the former two treatments reaching resistances of almost double that of the compost and vermi-castings treatments. Due to the relationship between soil water and resistance, as well as, soil salinity and resistance (Hillel 1980), and the absence of significant differences between treatments with regards to soil texture (clay, silt and sand), the differences in resistance between the inorganic mulch and the organic mulch treatments (excluding the woodchips treatment) could largely be due to differences in soil water, however, more so to do with salinity (data in Paper 2) (Hillel 1980). The control and woodchips treatments behaved in a similar fashion regarding soil water, as both treatments displayed lower soil water levels during the period in which soil was sampled for physical analysis. Whilst the geotextile fabric treatment had high soil water levels at times, due to large fluctuations in soil water levels in this treatment, it also had low soil water levels. These results therefore support the hypothesis that higher resistance values are associated with drier soils, which were experienced in the control and geotextile fabric treatments. However, the compost treatment had considerably lower soil water levels than the other treatment but high resistance values did not occur in this treatment. Hillel (1980) stated that resistance is directly affected by soluble salt concentration, where high soluble salt concentration results in low soil resistance. The organic mulching materials were analysed for salinity in March of 2012 and it was found that the vermi-castings mulching material had a significantly higher salinity (140.38 mS m^{-1}) compared to the compost and woodchips mulching materials and the compost mulching material had a higher salinity compared to the woodchips mulching material (87.17 mS m^{-1} and 84.92 mS m^{-1} respectively). It is therefore likely that the slightly higher salinity of the compost mulching material contributed to the reduction in resistance achieved by the compost treatment. It is therefore likely that the higher soil water content of the vermi-castings treatment, together with the higher salinity of the vermi-castings mulching material, resulted in the significantly lower resistance achieved by the vermi-castings treatment.

The only significant differences between treatments with regards to bulk density were found in the intermediate soil layer (10 – 30 cm) of the heavier soil site. The organic mulches had significantly lower bulk densities than the control treatment. This can be attributed to an increase in organic matter under the organic mulches, which is consistent with Hillel's (1980) remarks of increasing organic matter resulting in decreasing bulk density. The bulk densities found in both sites were slightly lower than normal bulk densities in loamy soils with $\rho_b = 1.2$ in the heavier soil as compared to an accepTable value of $\rho_b = 1.4$ and $\rho_b = 1.4$ was found in the lighter soil site as compared to an accepTable value of $\rho_b = 1.5$ (Hillel 1980).

Soil Temperature

Pregitzer et al. (2000) reported that the greatest fluctuations in soil temperature take place at the surface of the soil and decrease with depth. As a result, this study has focused on the impact of mulches on soil temperature in the top 10 cm of the soil.

It is evident from the results that soil temperatures fluctuated more in the lighter soil site compared to the heavier soil site. This is largely attributed to the nature of heavier soil, which has a higher water holding capacity compared to that of the lighter soil site, as seen in the soil water status of both soils, with the water content of the heavier soil varying between 40% and 45% and water content of the lighter soil varying between 15% and 35%). The resulting effect is that the greater the water content, the greater the buffering effect against dramatic temperature fluctuations. This is consistent with Lanini et al. (1988), who found reduced temperature fluctuations, with increased soil water content.

Over the two seasons (2011 – 2012), and in both soil types, the organic mulches, particularly the woodchips treatment in the heavier soil site and the vermi-castings treatment in the lighter soil site, kept the soils consistently warmer, with reduced fluctuations. This is consistent with the findings of Treder et al. (2004) in a trial conducted with woodchip mulches. These authors attributed a consistent response of different soils to different mulches to the influence of the mulch on soil water content. The woodchips treatment resulted in a lower and relatively constant soil water content, whereas the vermi-castings treatment achieved intermediate, but still relatively constant soil water contents. Warmer and more consistent temperatures where achieved by both treatments. The nature of the different soil types therefore affected the incorporation of these organic mulching materials in the soil and ultimately the organic matter contents of the soils, which in turn influences the water holding capacity and water status of the soils. It is also evident under our experimental conditions that the soil physical properties under organic mulches varied far less than the other treatments over the two seasons. This confirms the buffering properties of organic mulches against environmental extremes (Janick 1986), and is consistent with Fourie and Freitag's (2010) conclusions that surface mulching of a medium textured soil reduces the diurnal variation in temperature during the growing season.

The geotextile fabric treatment and the control treatment followed similar trends with regard to temperatures and fluctuations thereof in both soil types. This may be attributed to the thickness (approximately 3 mm) and woven nature of the geotextile fabric mulch, which provided limited insulation to the soil surface and thus made it as vulnerable to changing temperatures as an uncovered soil. It has been shown that bare soils are more susceptible to temperature fluctuations, especially at the surface (Pregitzer et al. 2000). The geotextile fabric treatment also fluctuated more than the control treatment, particularly in the heavier soil site, but also in the lighter soil site and this tendency was particularly evident during hotter parts of the season. The colour of the fabric may have contributed to the higher temperatures and fluctuations thereof, as black plastics heat up quicker than lighter coloured plastics or organic mulching materials (Janick 1986). In the heavier soil site, however, a higher soil water content was recorded in the top 10 cm of the geotextile fabric treatment. Due to the buffering effects of higher water levels in the soil, the temperature fluctuations may have been more pronounced had the soil water been less.

Soil water

In the heavier soil site, the compost treatment resulted in higher average soil water contents compared to that of the other treatments in the 10 cm soil layer, but t had lower soil water levels with increasing soil depth compared to the other treatments. Haynes (1980) and Wolstenholme et al. (1996) reported that organic ground covers increase the organic matter on and near the soil surface. This improves, in particular, the physical properties (e.g. a decrease in bulk density) (Hillel 1980), which increases the water holding capacity of the soil in that area and reduces percolation to deeper layers. The compost treatment therefore kept water in the upper soil layers and reduced water movement to the lower layers. Although no significant differences between treatments were found with regard to the bulk density in the heavier soil site, the compost treatment resulted in the lowest bulk density in the 0 – 10 cm soil layer but was not significant. This suggests that there was more organic matter in the upper soil layer of the heavier soil site as a result of the compost treatment, which could explain the high soil water content near the soil surface which was not found with depth. Due to the heavy nature of the soil in this site, incorporation of the compost material into the soil was limited, which is confirmed by the increase in bulk density with depth. This may explain the decline in high soil water levels with depth, resulting in lower soil water levels compared to the other treatments in the deeper soil layers. In the lighter soil site however, the compost treatment resulted in consistently higher soil water levels down the profile. In contrast to the heavier soil site, the lighter nature of the soil may have allowed for more compost incorporation into the soil, and thus higher organic matter levels in the deeper soil layers. Therefore the higher soil water levels in the deeper soils as a result of the compost treatment suggests increased organic matter levels in the deeper soil layers.

The woodchips treatment frequently resulted in the lowest soil water content at both sites. However, in the heavier soil site it had intermediate soil water levels in the 10 cm soil layer and the lowest soil water level in the deeper soil layers; and in the lighter soil site, it had the lowest soil water level in the 10 cm soil layer and intermediate soil water levels in the deeper soil layers. The lower soil water content in the deeper layers may be as a result of less organic matter in the soil with depth. In the lighter soil site, and the heavier soil site to a lesser extent, the woodchips treatment also frequently resulted in higher temperatures in the soil which is an effect of lower soil water levels and confirms these results. Zak et al. (1999) reported that water stress is often accompanied by increased soil temperatures. Although the trees were far from water stressed, the increased temperature as a result of the woodchips treatment in the lighter soil site may have been attributed to the lower soil water levels.

In both sites, the geotextile fabric and the vermi-castings treatments resulted in higher or intermediate soil water levels at all of the analysed depths compared to the other treatments. A primary benefit of mulching in orchards is soil water conservation, which is largely a result of reduced evaporation from the surface (Wolstenholme et al. 1996). This was supported by Baver et al. (1972) and Haynes (1980) who noted that mulches protect the soil surface from direct sun rays and wind currents and thus reduce evaporative losses. The higher soil water levels found in the geotextile fabric and vermi-castings treatments can therefore be attributed one of the primary purposes of the mulching practice mentioned above.

Haynes (1980) stated that soils under clean cultivation run the risk of the breakdown of soil structure, which is associated with continued cultivation, which in turn results in decreased water holding capacity. In both sites, the control treatment resulted in higher to intermediate soil water levels in the upper soil layers, but had lower soil water levels in the deeper soil layers compared to the other treatments. The higher soil water levels in the upper layers of the soil in the control treatment may have been as a result of continued irrigation, keeping the top soil layers wet, and the lower soil water levels in the deeper soils may be attributed to the lack of water holding capacity in the soil as a result of the effects of clean cultivation on physical properties.

Conclusion

Results from this study confirmed that the impact of the various mulches on soil physical properties is dependent on the soil type and should be kept in mind when mulching is considered.

The compost treatment was successful in improving physical characteristics of the soil in the heavier soil site, and achieved intermediate bulk densities (lower than the control and geotextile fabric treatments), but low resistances. However, the same positive effects of this mulch were not observed in the lighter soil site. The compost treatment was efficient in reducing temperature fluctuation during the season in both sites. However, other organic mulch treatments were more successful in maintaining higher soil temperatures during the season. In the heavier soil site, higher temperatures occurred in the compost treatment during warmer periods which were accompanied by lower soil water levels. In contrast, the compost treatment showed lower temperatures and higher soil water levels in the lighter soil site. Therefore the compost treatment's performance as a mulch is reliant on soil type and can have a primary or secondary effect, or both, on soil temperature and soil water, which in turn can impact one another.

The geotextile fabric treatment did not improve the physical characteristics of the heavier soil site as much as the compost treatment. Soils in this treatment had an intermediate bulk density which was lower than the control treatment. Once again there was very little impact of the geotextile fabric treatment on the physical properties of the lighter soil site. NoTable fluctuations in temperatures occurred as a result of the geotextile fabric treatment in the heavier soil site, particularly during periods of hot days and cool nights which are important for 'Cripps' Pink' fruit colour development. Although temperatures in this site, under the geotextile fabric mulch, fluctuated considerably, soil water levels were higher in the upper layers of the soil compared to the other treatments, which is an unusual accompaniment for fluctuating temperatures. The higher temperatures and fluctuations may be due to the colour and thickness of the fabric, heating up quickly as a result of attracting more radiation, but failing to retain the heat as a result of being thin and lacking buffering properties. Thus, due to the lack of physical improvement in the soil, water could have been trapped in the upper layers of the soil in the heavier soil site as a result of physical breakdown of soil structure. This leads to compaction, known to occur under plastic type mulches. In the lighter soil site, soil water levels were lower under the geotextile fabric mulch, suggesting that more drainage was occurring and physical characteristics of the soil did not deteriorate as in the heavier soil site.

The vermi-castings treatment was effective in improving physical characteristics of the heavier soil site as it resulted in intermediate bulk densities (lower than the control and geotextile faberic), however low resistances. Due to the improved physical characteristics of the soil, soil water and temperature levels were stabilized and remained intermediate compared to the other treatments, for both sites. The vermi-castings treatment was also most effective in preventing extreme temperature fluctuations and soil water contents in the lighter soil site. The primary attributes to mulching (temperature stabilization and water conservation) were therefore achieved by the vermi-castings treatment in both sites.

In contrast to the other mulch treatments, the woodchips treatment resulted in favourably high resistances in the heavier soil site, and achieved a low bulk density. It therefore resulted in the greatest improvement in the physical conditions of the soil. The woodchips treatment was also successful in stabilizing temperature fluctuations and warming the soil throughout the season, benefiting fine root growth. In the heavier soil site this resulted in intermediate soil water levels, but low soil water levels occurred in the lighter soil site.

In conclusion, organic mulches were more effective in improving the physical root environment in the heavier soil, than in the lighter soil site. The woodchips mulch was superior in ameliorating the root environment and this outcome was not limited to the heavier soil. The compost and vermi-castings mulches did however result in lower resistances which can be attributed to the salinity content of the mulching material (data in Paper 2). The inorganic mulch was largely unsuccessful in improving the physical environment of both sites. These results confirmed that the choice of mulch must be based on the primary requirements of the specific site, i.e. water conservation or improvement of soil structure, and physical capabilities of the mulch.

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Table 1 Soil texture analysis for the heavier and lighter soil sites

Site	Soil Classification	Stone Fraction (Vol %)	Clay (%)	Silt (%)	Sand (%)
Heavier soil	Clovelly form	3.3	1.273333	4.05	94.67667
Lighter soil	Tukulu form	4.783333	1.47	2.863333	95.66667

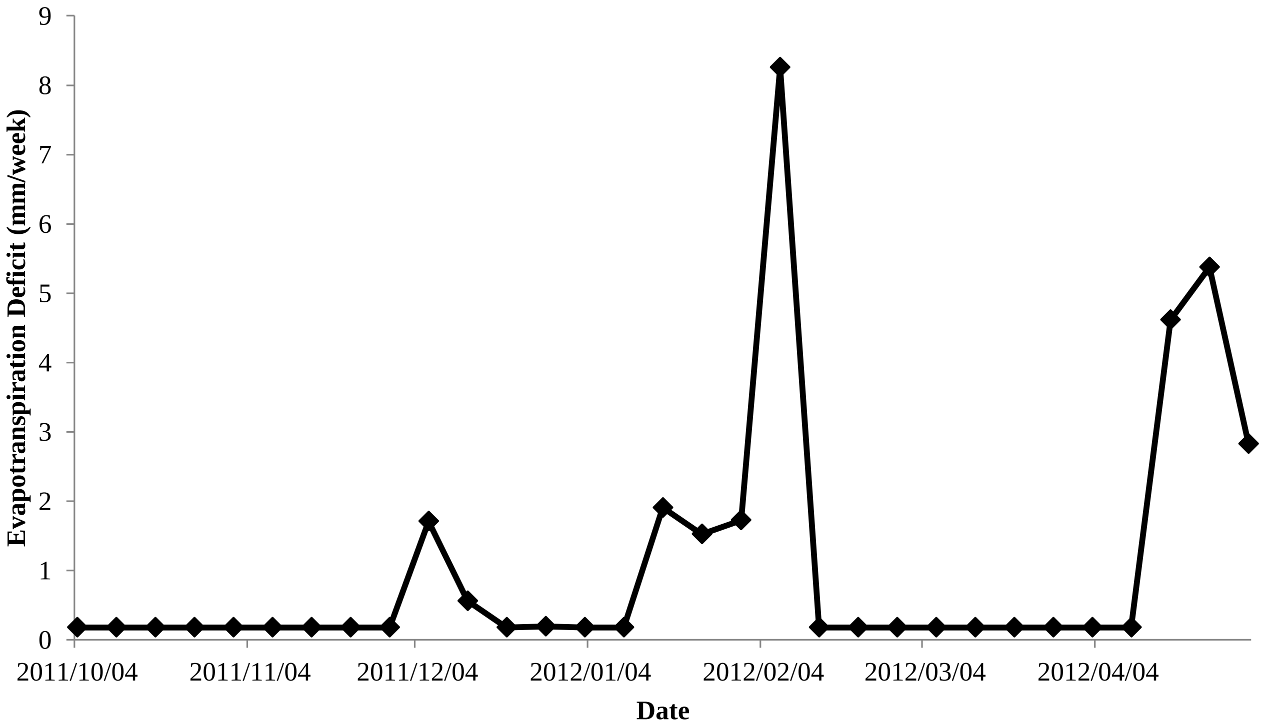

Fig. 1. Evapotranspiration deficit (mm) per week from October 2011 to April 2012 in a hectare area including both sites (www.fruitlook.co.za)

Table 2 Physical analysis at 0 – 10 cm depth in the heavier soil site performed in May 2012

Treatment	Bulk Density (kg/ℓ)	Resistance (Ohm)
Compost	1.18^{ns}	1942.50^{b}
Control	1.25	3052.50^{a}
Geotextile Fabric	1.24	3117.50^{a}
Vermi-castings	1.20	1465.00^{b}
Woodchips	1.37	2782.50^{a}
p-value	0.5592	0.0013
LSD	0.26	751.23

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 3 Physical analysis at 0 – 10 cm depth in the lighter soil site performed in May 2012

Treatment	Bulk Density (kg/ℓ)	Resistance (Ohm)
Compost	1.42^{ns}	3480.00^{ns}
Control	1.45	4010.00
Geotextile Fabric	1.43	3005.00
Vermi-castings	1.40	2413.00
Woodchips	1.38	2493.00
p-value	0.2121	0.5200
LSD	0.06	2254.30

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 4 Physical analysis at 10 – 30 cm depth in the heavier soil site performed in May 2012

Treatment	Bulk Density (kg/ℓ)	Resistance (Ohm)
Compost	1.215^{ABC}	2542.50^{b}
Control	1.295^{A}	3765.00^{a}
Geotextile Fabric	1.270^{AB}	3967.50^{a}
Vermi-castings	1.200^{BC}	1940.00^{b}
Woodchips	1.172^{C}	3312.50^{a}
p-value	0.0558	0.0001
LSD	0.09	673.46

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 5 Physical analysis at 10 – 30 cm depth in the lighter soil site performed in May 2012

Treatment	Bulk Density (kg/ℓ)	Resistance (Ohm)
Compost	1.44[ns]	4525.00[ns]
Control	1.46	4738.00
Geotextile Fabric	1.40	3803.00
Vermi-castings	1.42	3028.00
Woodchips	1.43	3438.00
p-value	0.4457	0.7067
LSD	0.07	3009.70

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 6 Physical analysis at 30 – 50 cm depth in the heavier soil site performed in May 2012

Treatment	Bulk Density (kg/ℓ)	Resistance (Ohm)
Compost	1.22[ns]	2827.50[b]
Control	1.32	4455.00[a]
Geotextile Fabric	1.24	4152.50[a]
Vermi-castings	1.26	2345.00[b]
Woodchips	1.23	3375.00[ab]
p-value	0.1485	0.0179
LSD	0.09	1272.20

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 7 Physical analysis at 30 – 50 cm depth in the lighter soil site performed in May 2012

Treatment	Bulk Density (kg/ℓ)	Resistance (Ohm)
Compost	1.45[ns]	4743.00[ns]
Control	1.46	4420.00
Geotextile Fabric	1.41	3933.00
Vermi-castings	1.44	3213.00
Woodchips	1.41	4293.00
p-value	0.6656	0.7824
LSD	0.10	2736.40

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

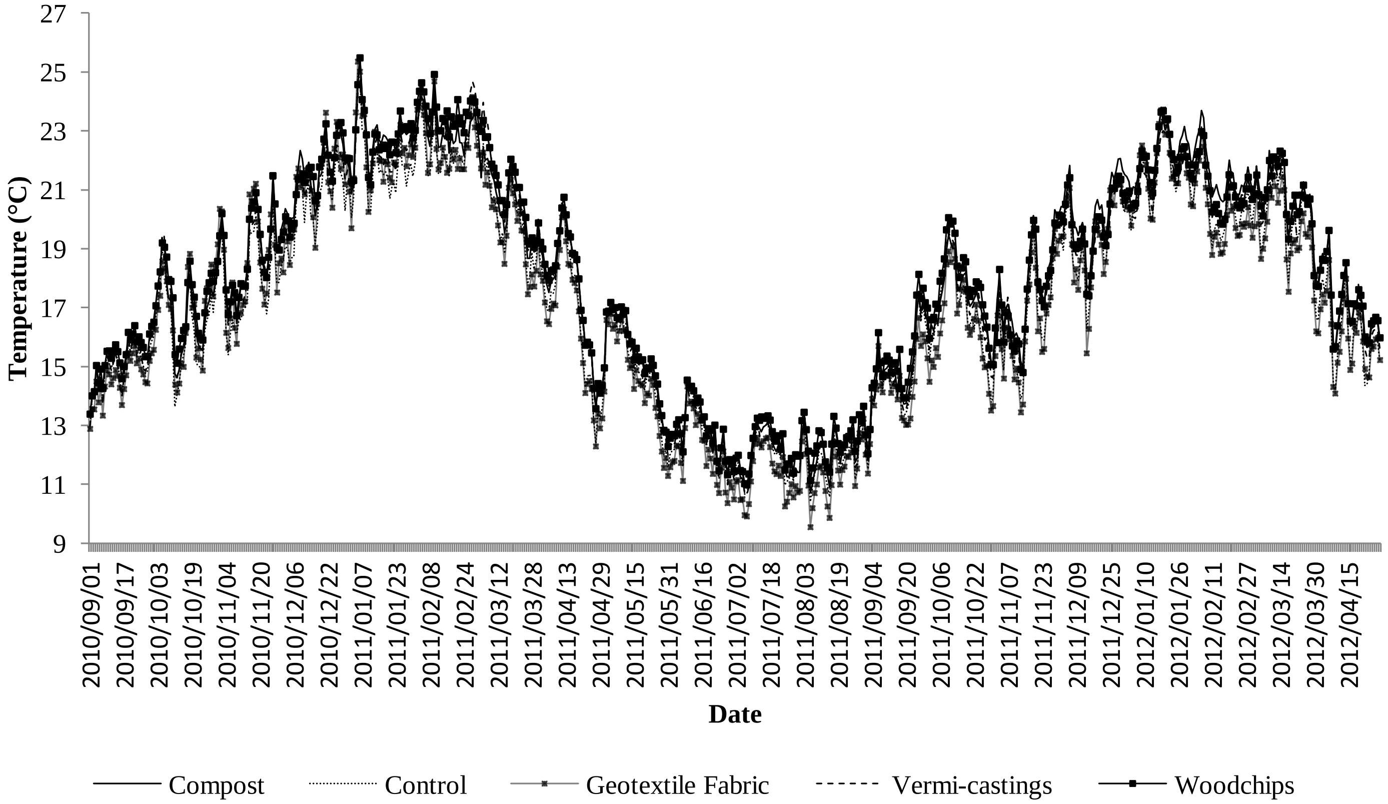

Fig. 2 Average soil temperature over two seasons (1 Sept 2010 – 30 April 2012) at 10 cm depth of one replicate per treatment in the heavier soil site

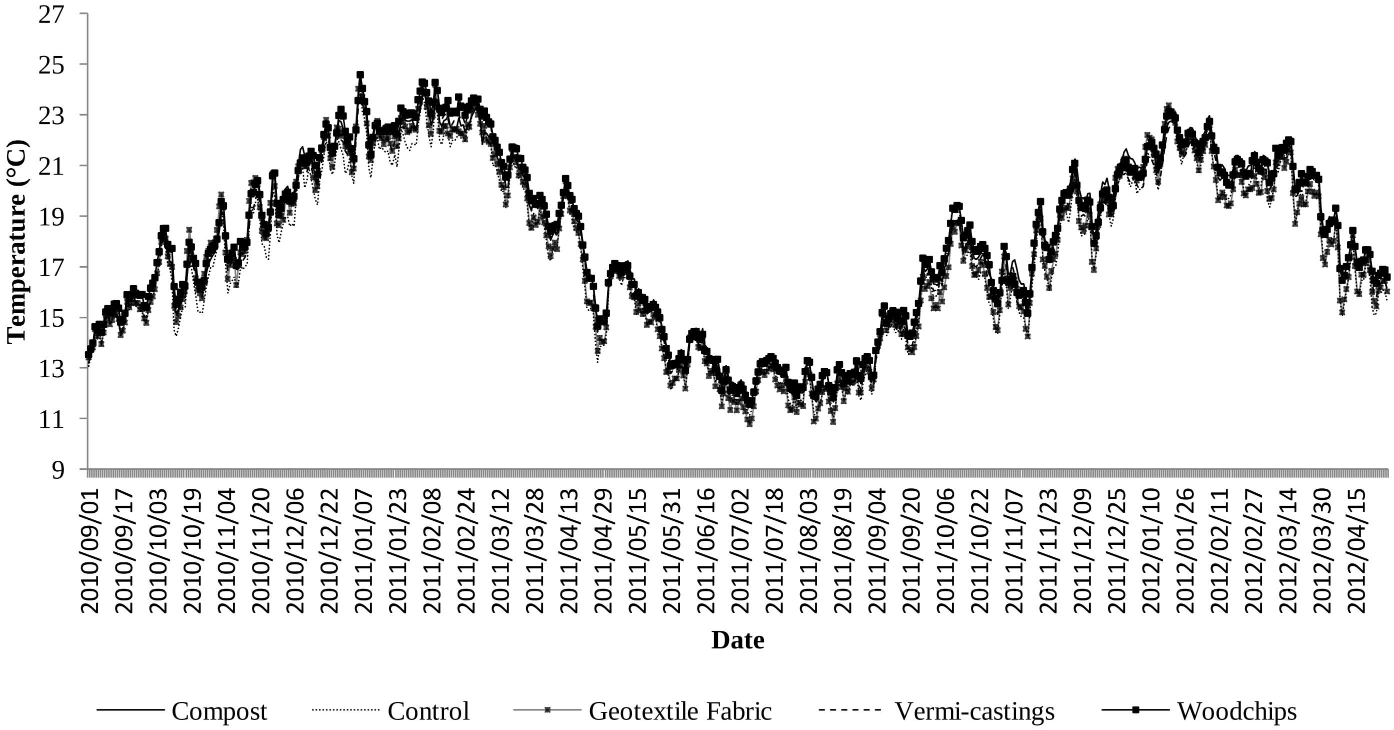

Fig. 3 Average soil temperature over two seasons (1 Sept 2010 – 30 April 2012) at 20 cm depth of one replicate per treatment in the heavier soil site

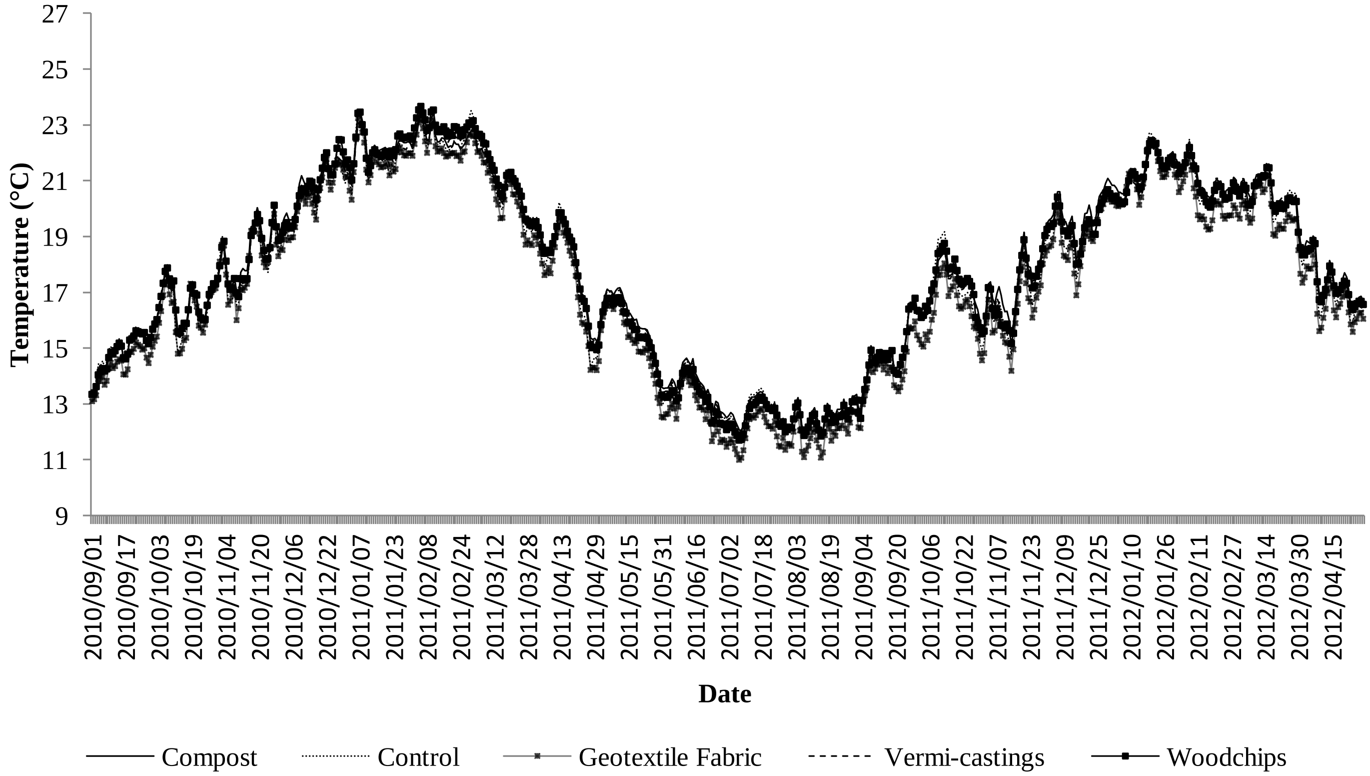

Fig. 4 Average soil temperature over two seasons (1 Sept 2010 – 30 April 2012) at 30 cm depth of one replicate per treatment in the heavier soil site

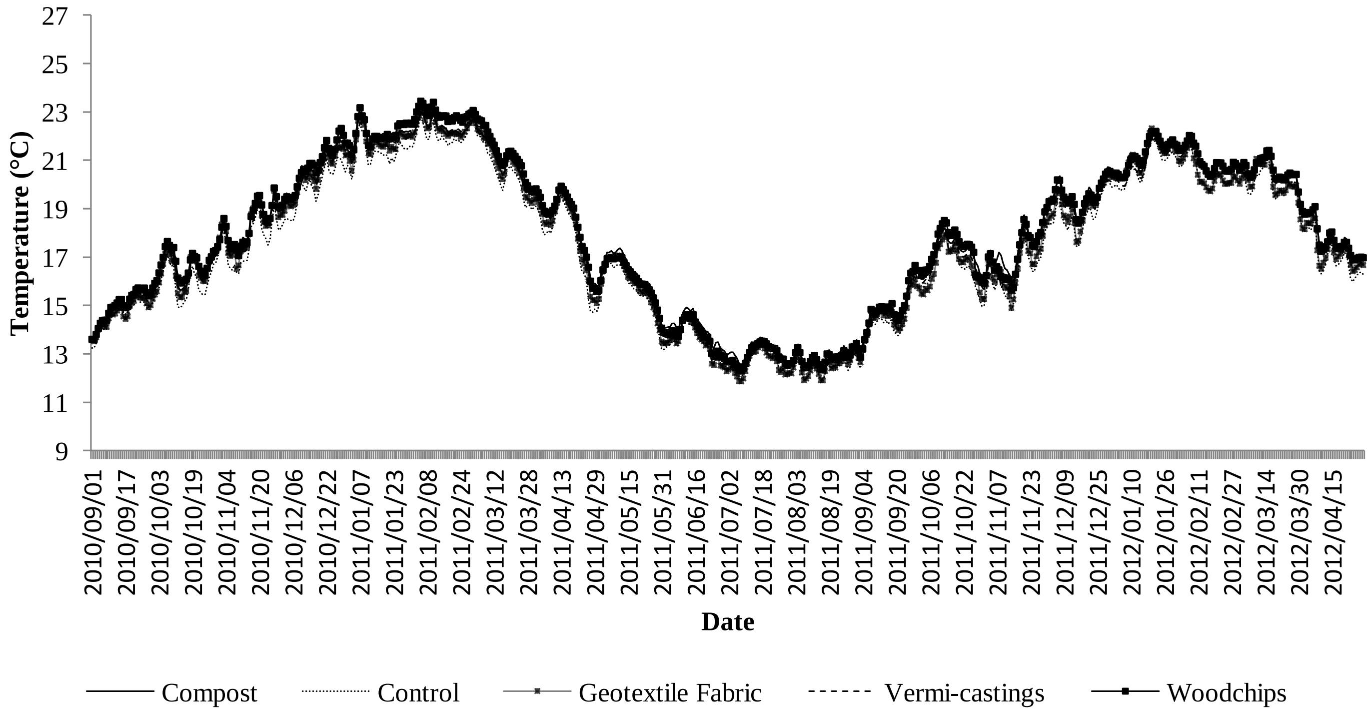

Fig. 5 Average soil temperature over two seasons (1 Sept 2010 – 30 April 2012) at 40 cm depth of one replicate per treatment in the heavier soil site

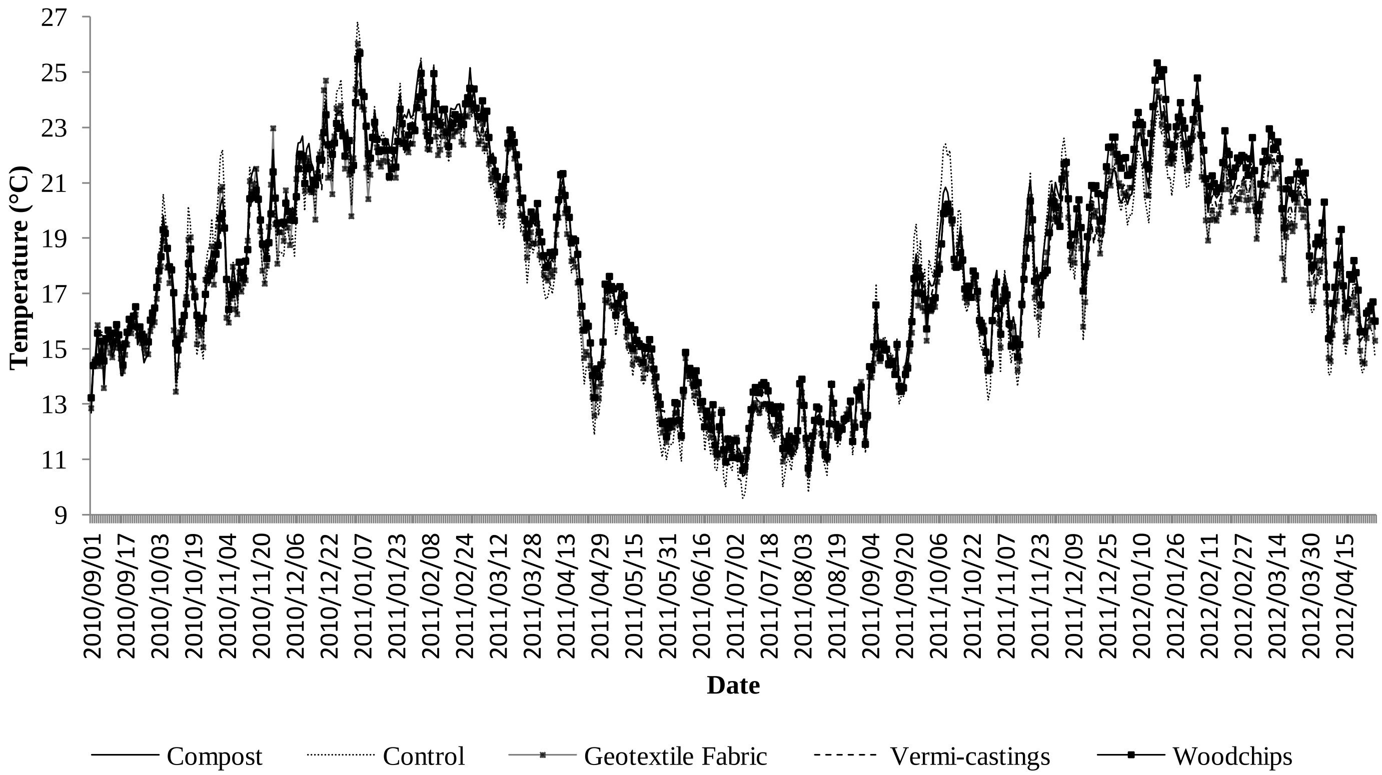

Fig. 6 Average soil temperature over two seasons (1 Sept 2010 – 30 April 2012) at 10 cm depth of one replicate per treatment in the lighter soil site

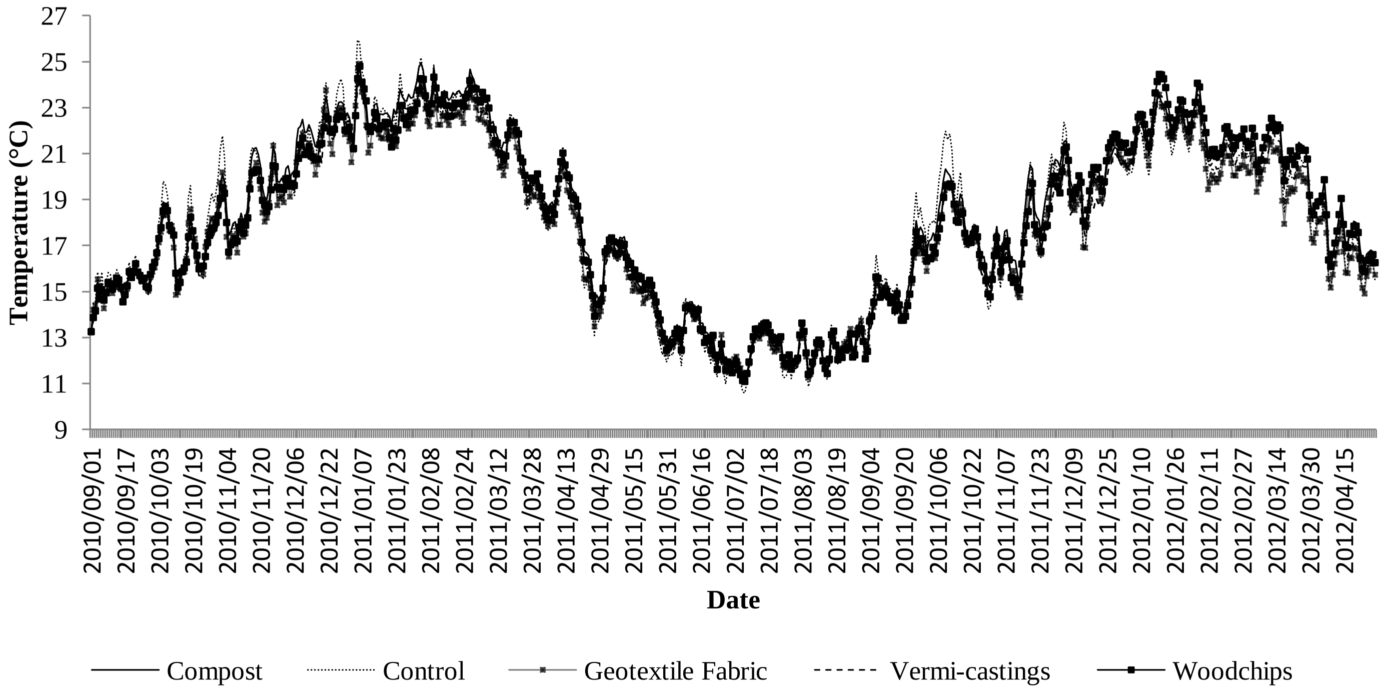

Fig. 7 Average soil temperature over two seasons (1 Sept 2010 – 30 April 2012) at 20 cm depth of one replicate per treatment in the lighter soil site

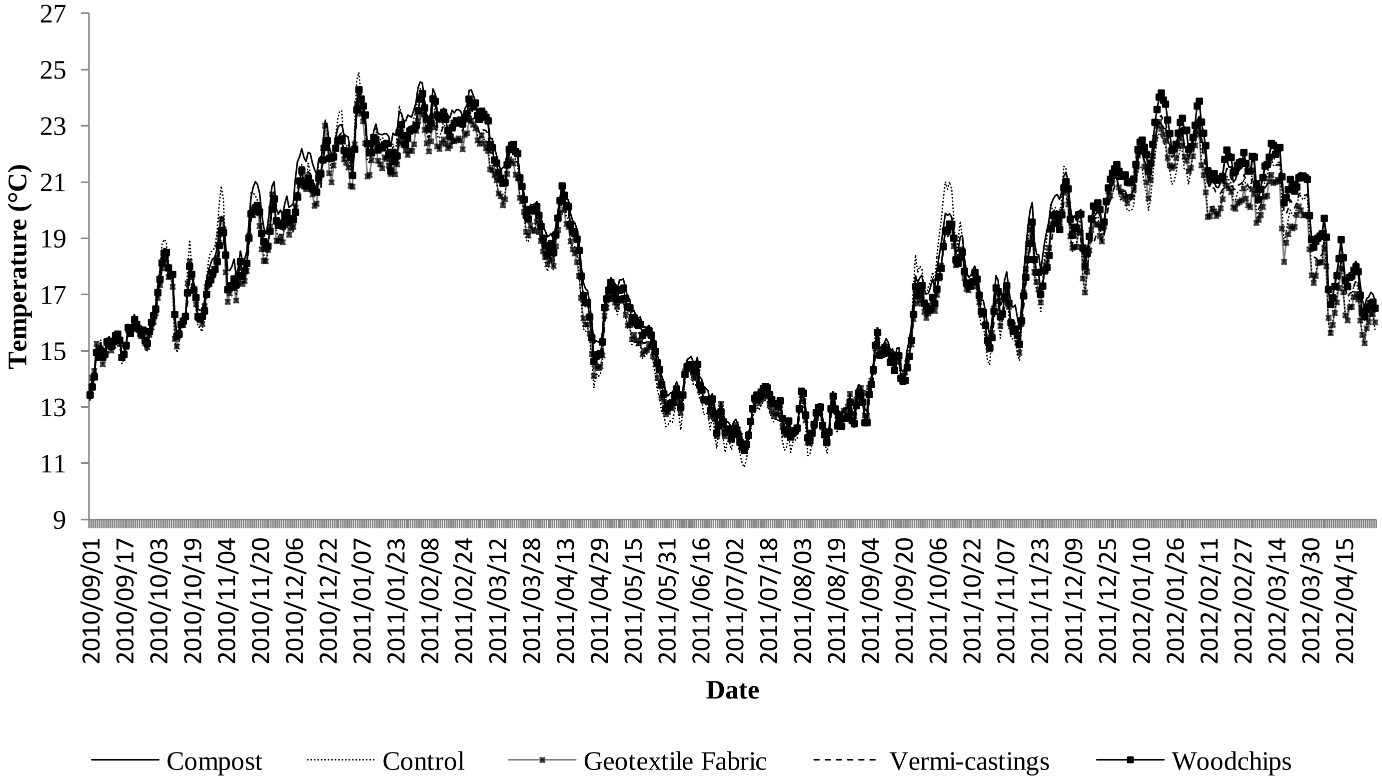

Fig. 8 Average soil temperature over two seasons (1 Sept 2010 – 30 April 2012) at 30 cm depth of one replicate per treatment in the lighter soil site

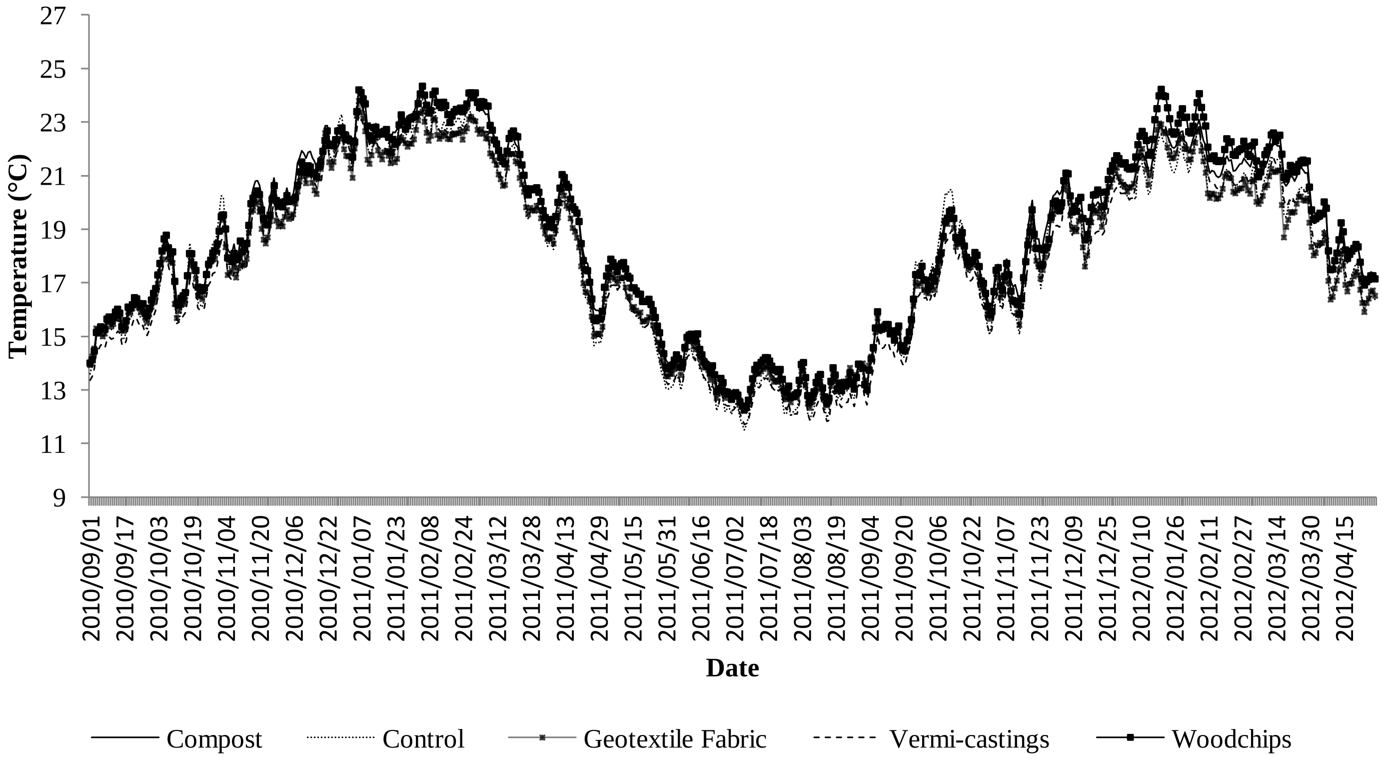

Fig. 9 Average soil temperature over two seasons (1 Sept 2010 – 30 April 2012) at 40 cm depth of one replicate per treatment in the lighter soil site

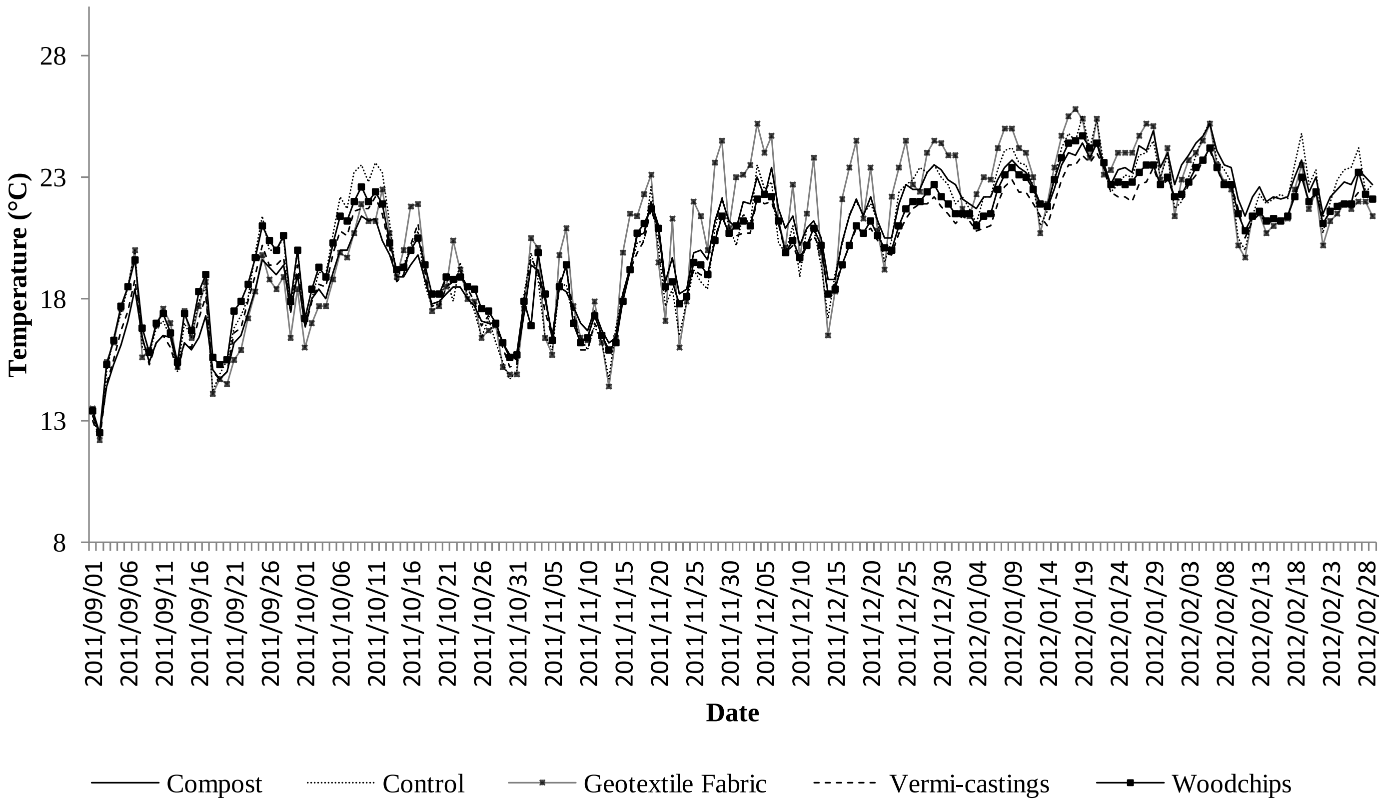

Fig. 10 Maximum daily temperatures at 10 cm depth of the profile of one replicate per treatment in the heavier soil site during the summer months (01 September 2011 – 28 February 2012)

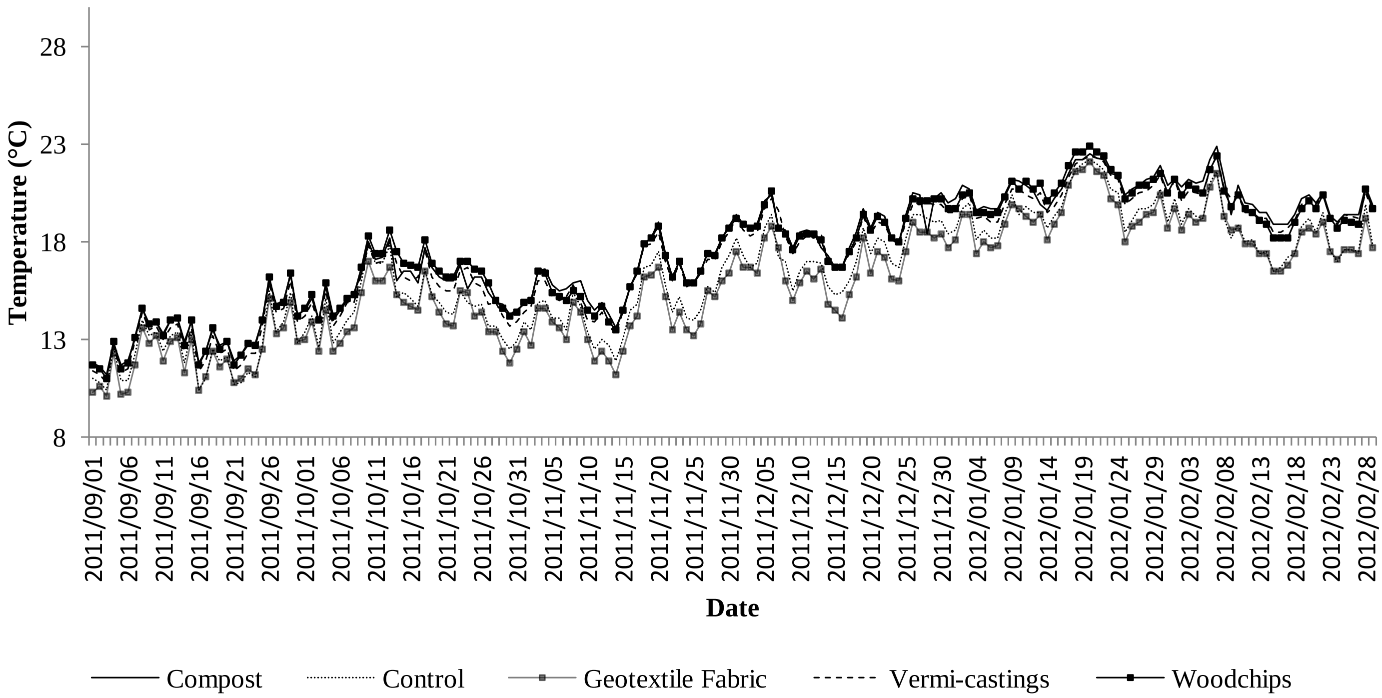

Fig. 11 Minimum daily temperatures at 10 cm depth of the profile of one replicate per treatment in the heavier soil site during the summer months (01 September 2011 – 28 February 2012)

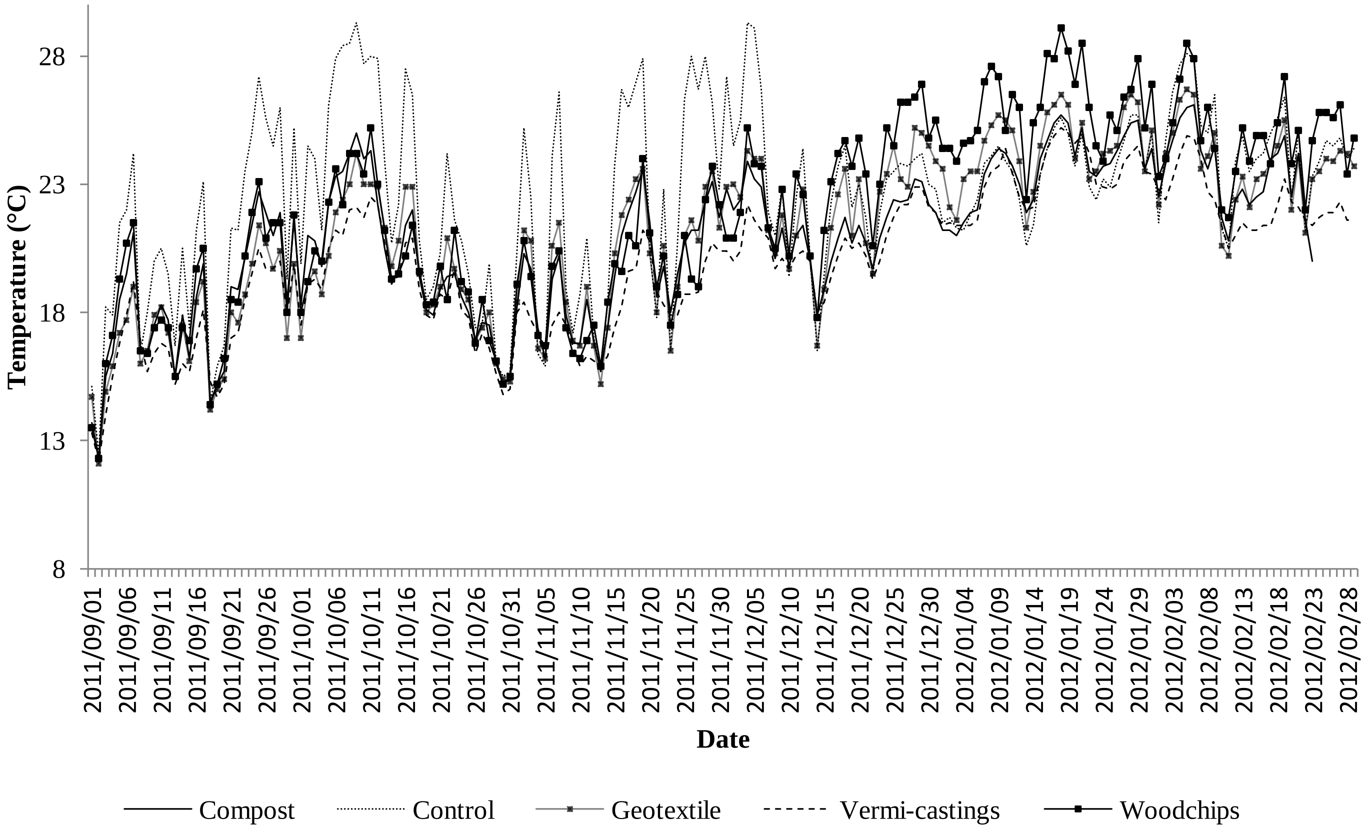

Fig. 12 Maximum daily temperatures at 10 cm depth of the profile of one replicate per treatment in the lighter soil site during the summer months (01 September 2011 – 28 February 2012)

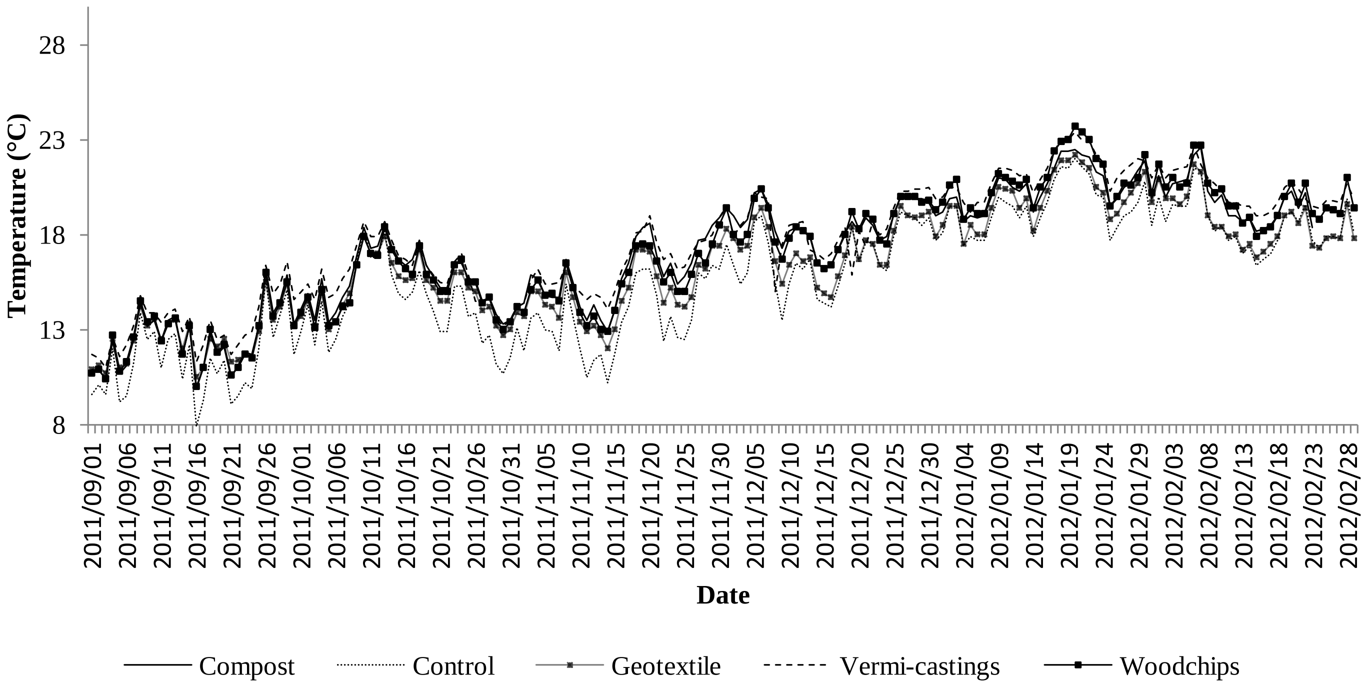

Fig. 13 Minimum daily temperatures at 10 cm depth of the profile of one replicate per treatment in the lighter soil site during the summer months (01 September 2011 – 28 February 2012)

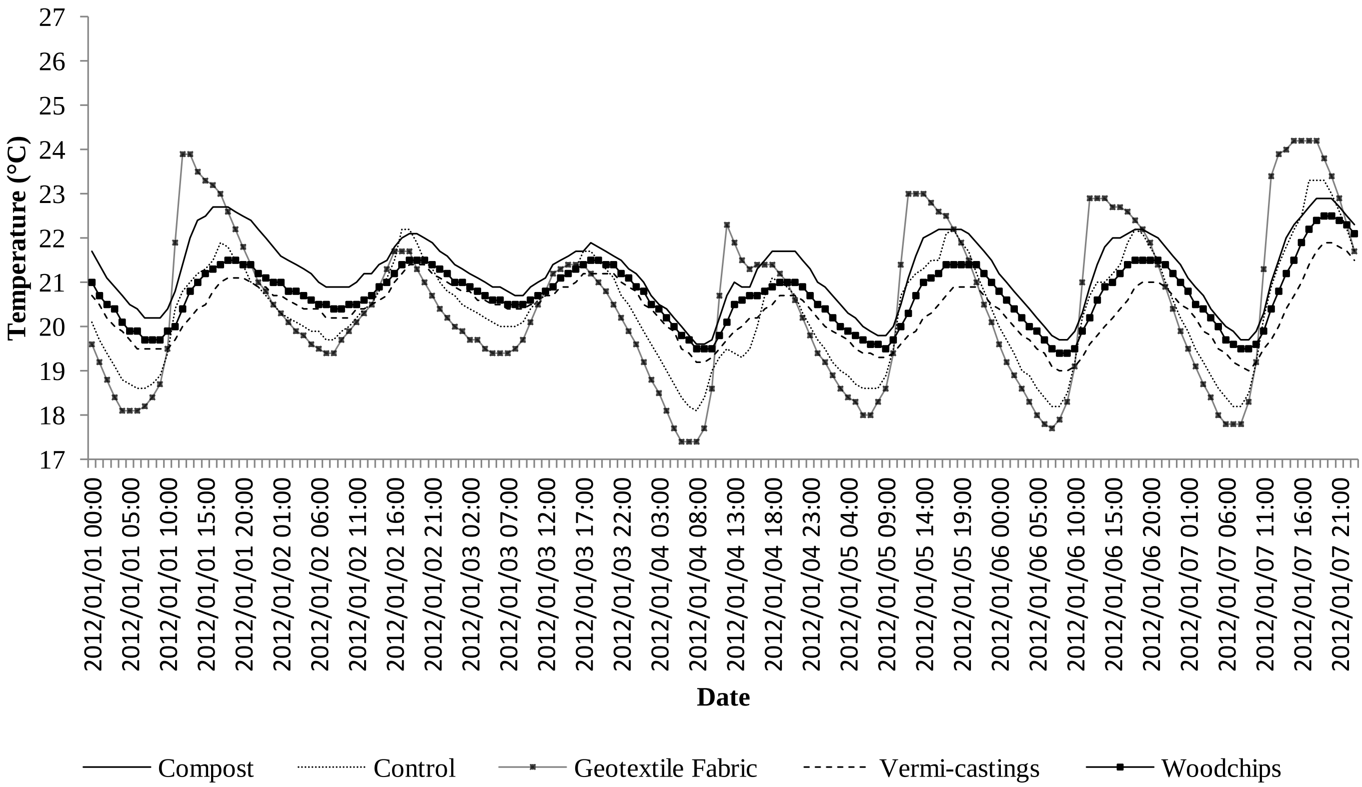

Fig. 14 Hourly temperature at 10 cm depth of the profile of one replicate per treatment in the heavier soil site during the first week of January 2012 (01 January 2012, 00h00 – 07 January 2012, 00h00)

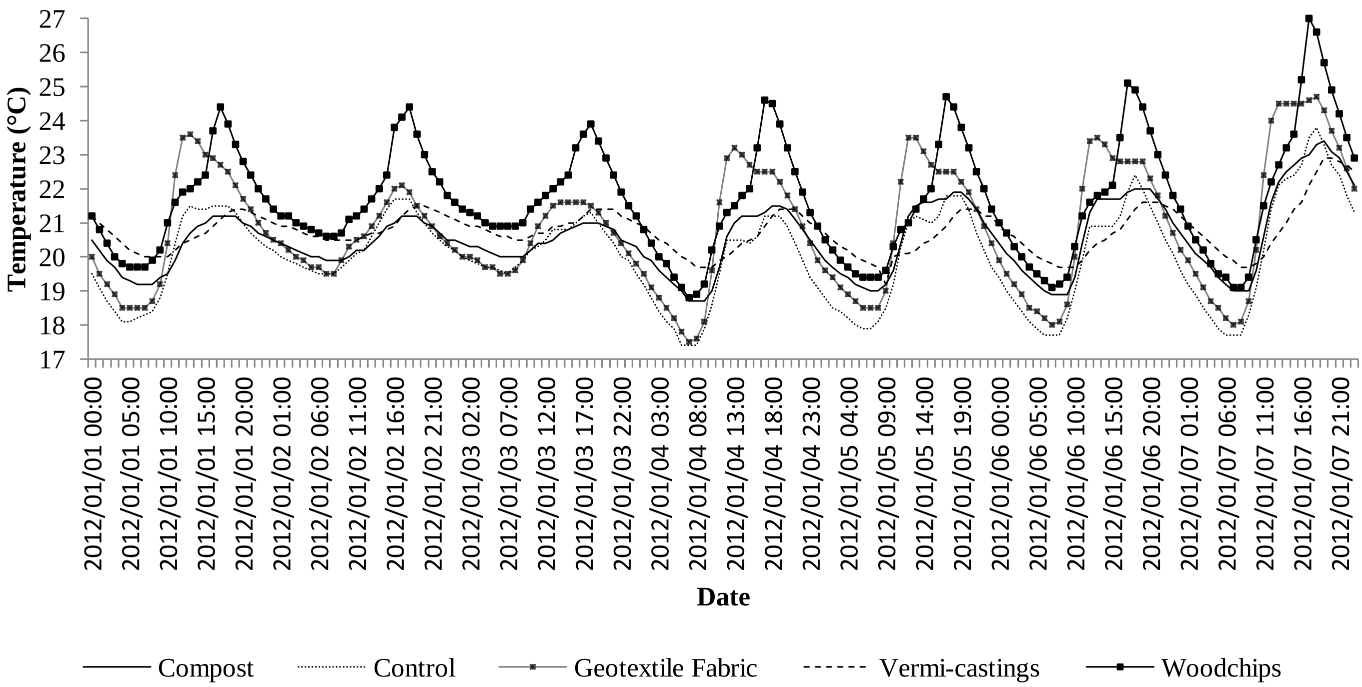

Fig. 15 Hourly temperature at 10 cm depth of the profile of one replicate per treatment in the lighter soil site during the first week of January 2012 (01 January 2012, 00h00 – 07 January 2012, 00h00)

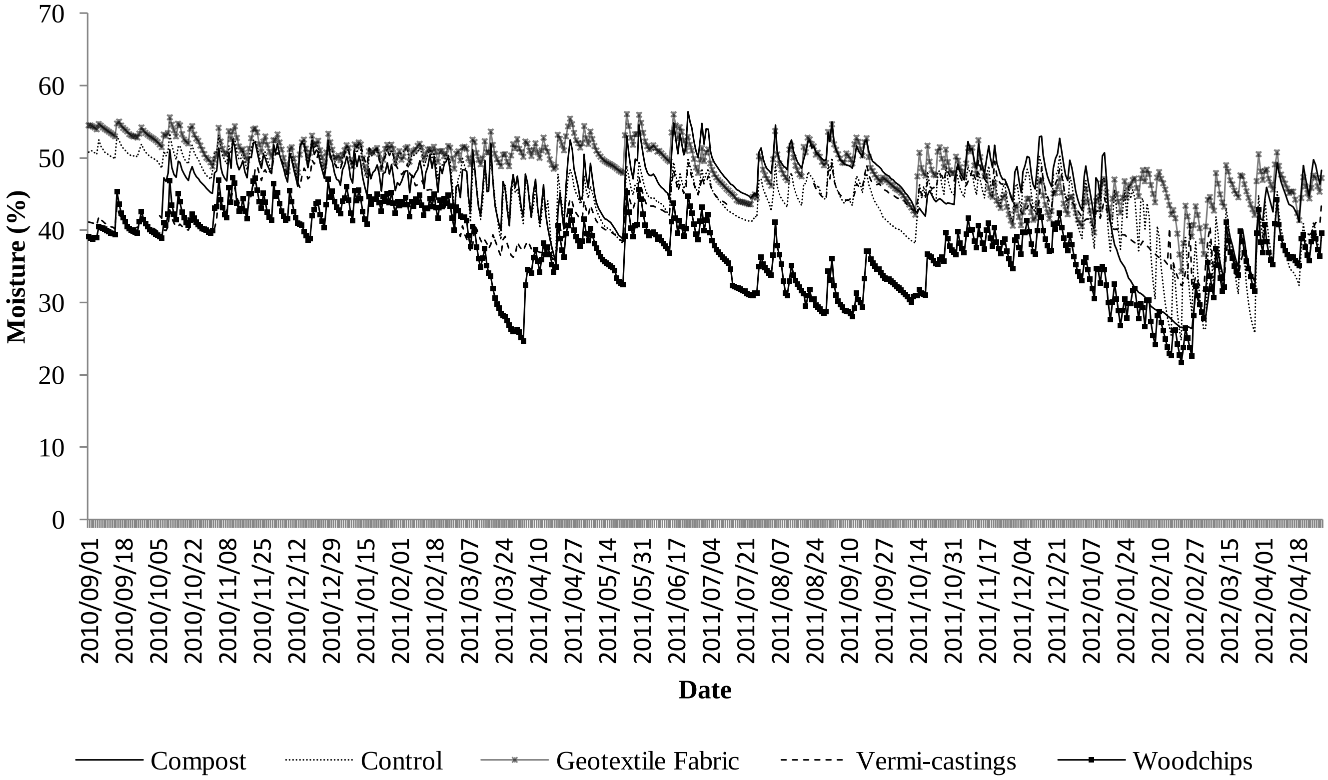

Fig. 16 Average soil water over two seasons (1 Sept 2010 – 30 April 2012) at 10 cm depth of one replicate per treatment in the heavier soil site

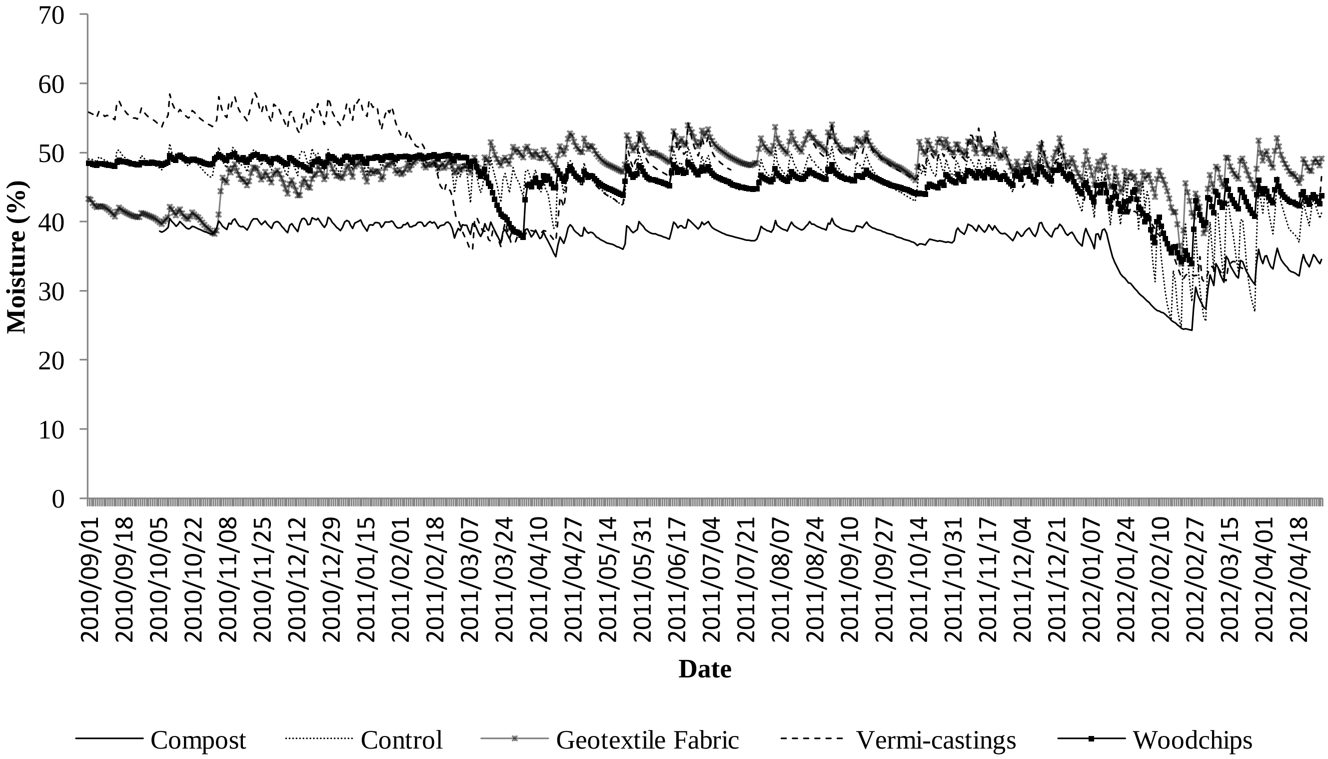

Fig. 17 Average soil water over two seasons (1 Sept 2010 – 30 April 2012) at 20 cm depth of one replicate per treatment in the heavier soil site

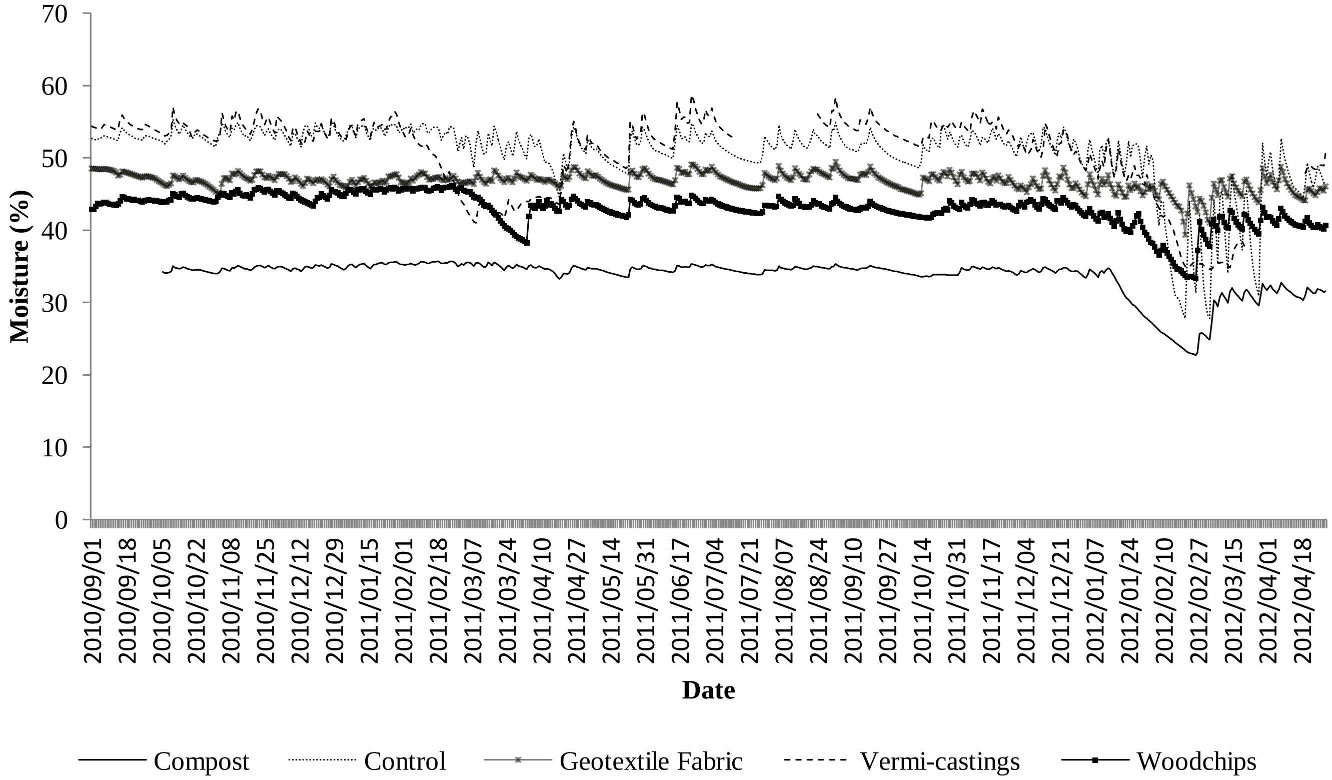

Fig. 18 Average soil water over two seasons (1 Sept 2010 – 30 April 2012) at 30 cm depth of one replicate per treatment in the heavier soil site

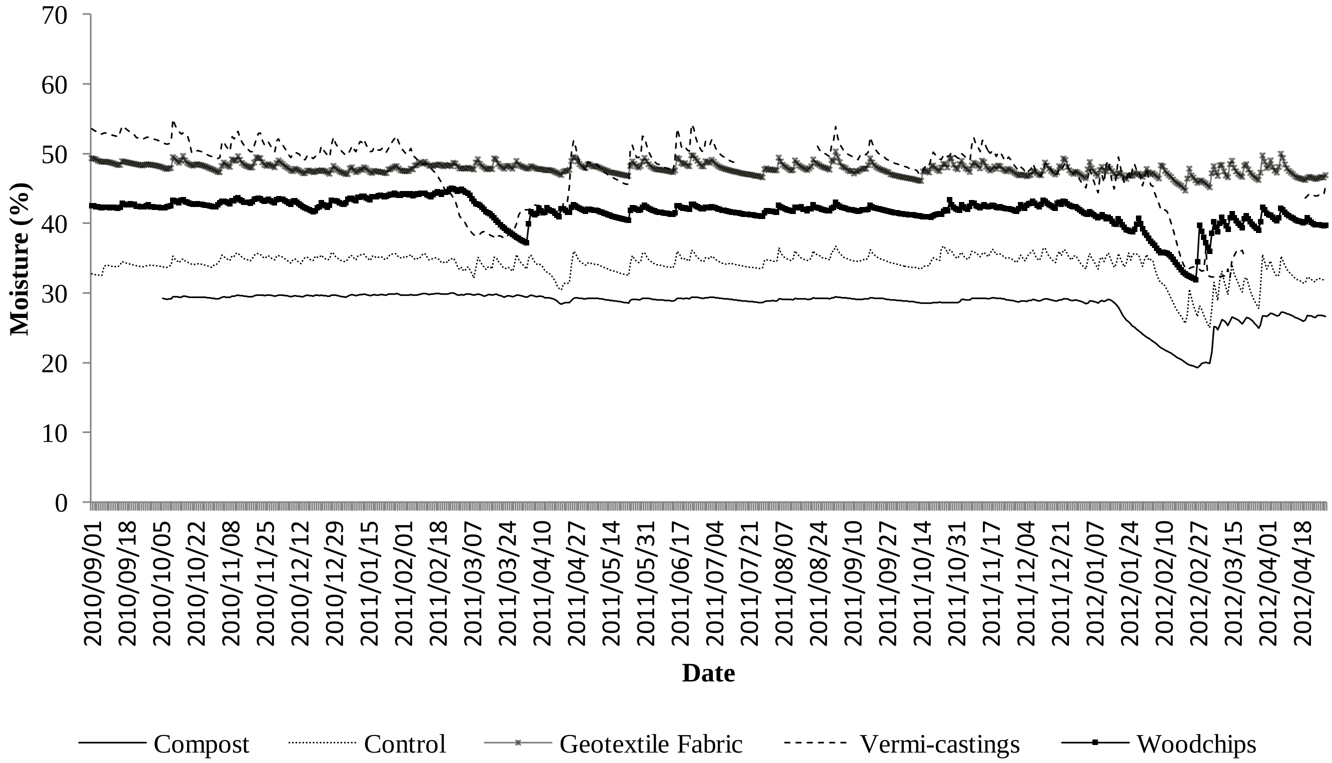

Fig. 19 Average soil water over two seasons (1 Sept 2010 – 30 April 2012) at 40 cm depth of one replicate per treatment in the heavier soil site

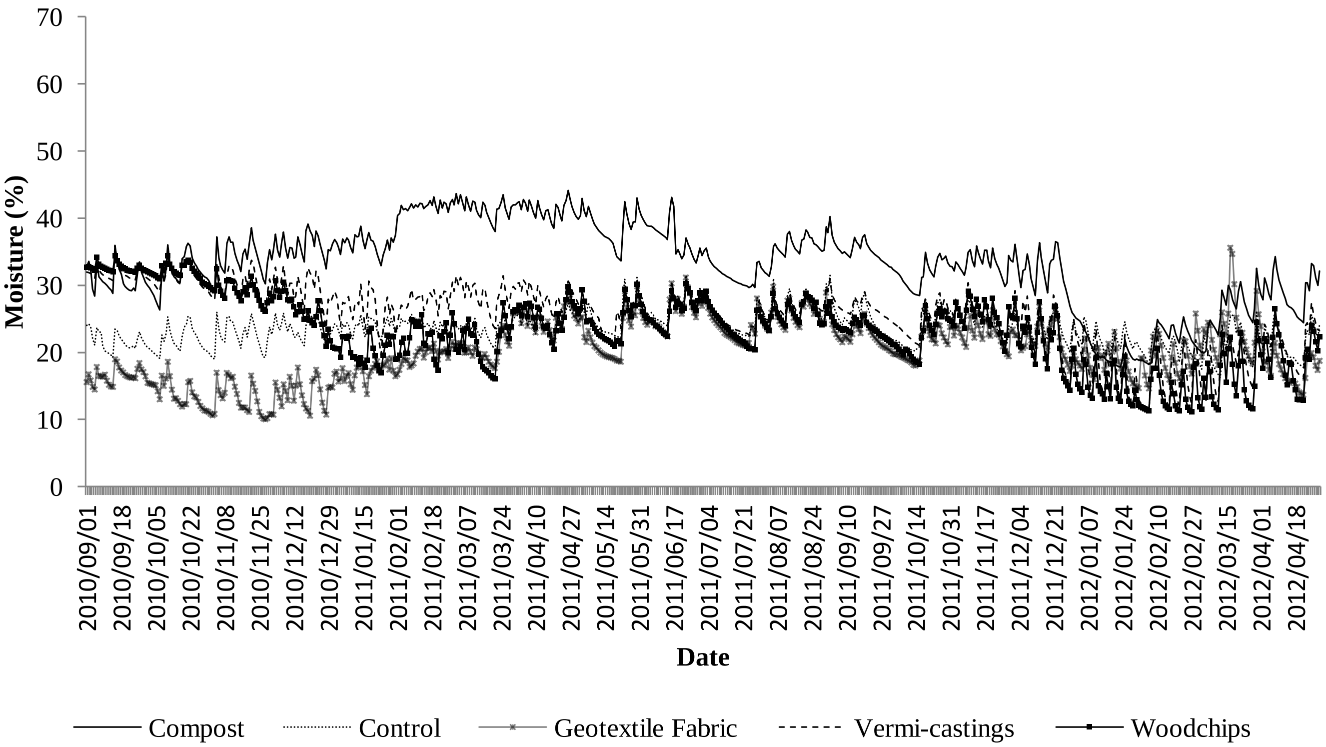

Fig. 20 Average soil water over two seasons (1 Sept 2010 – 30 April 2012) at 10 cm depth of one replicate per treatment in the lighter soil site

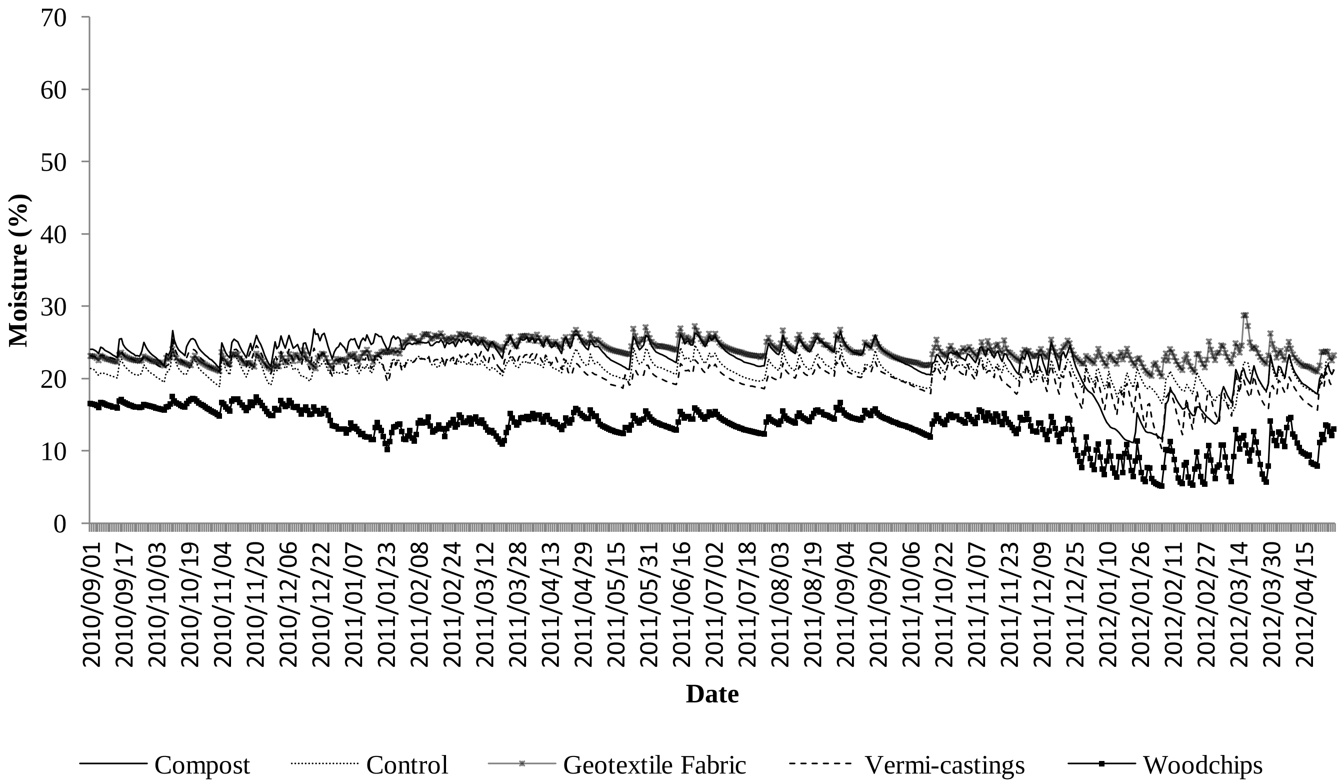

Fig. 21 Average soil water over two seasons (1 Sept 2010 – 30 April 2012) at 20 cm depth of one replicate per treatment in the lighter soil site

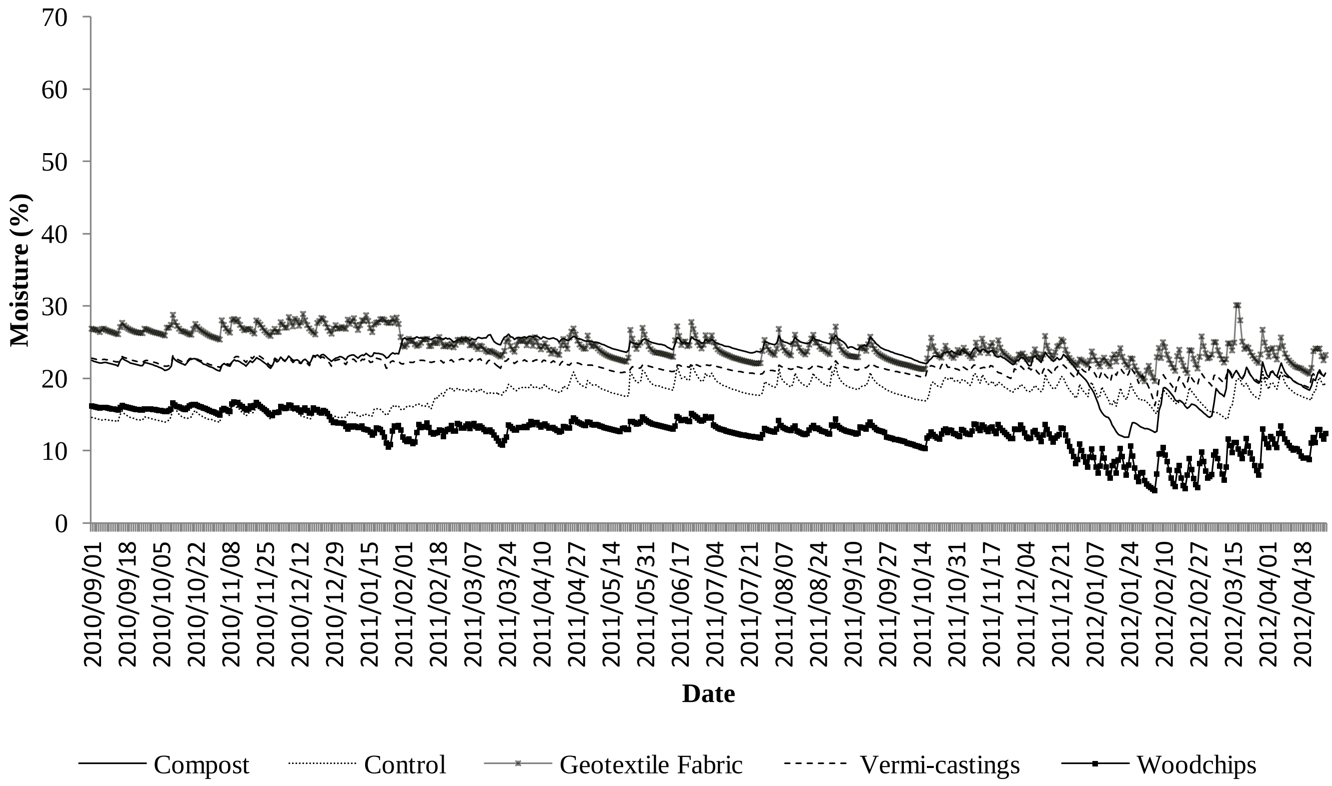

Fig. 22 Average soil water over two seasons (1 Sept 2010 – 30 April 2012) at 30 cm depth of one replicate per treatment in the lighter soil site

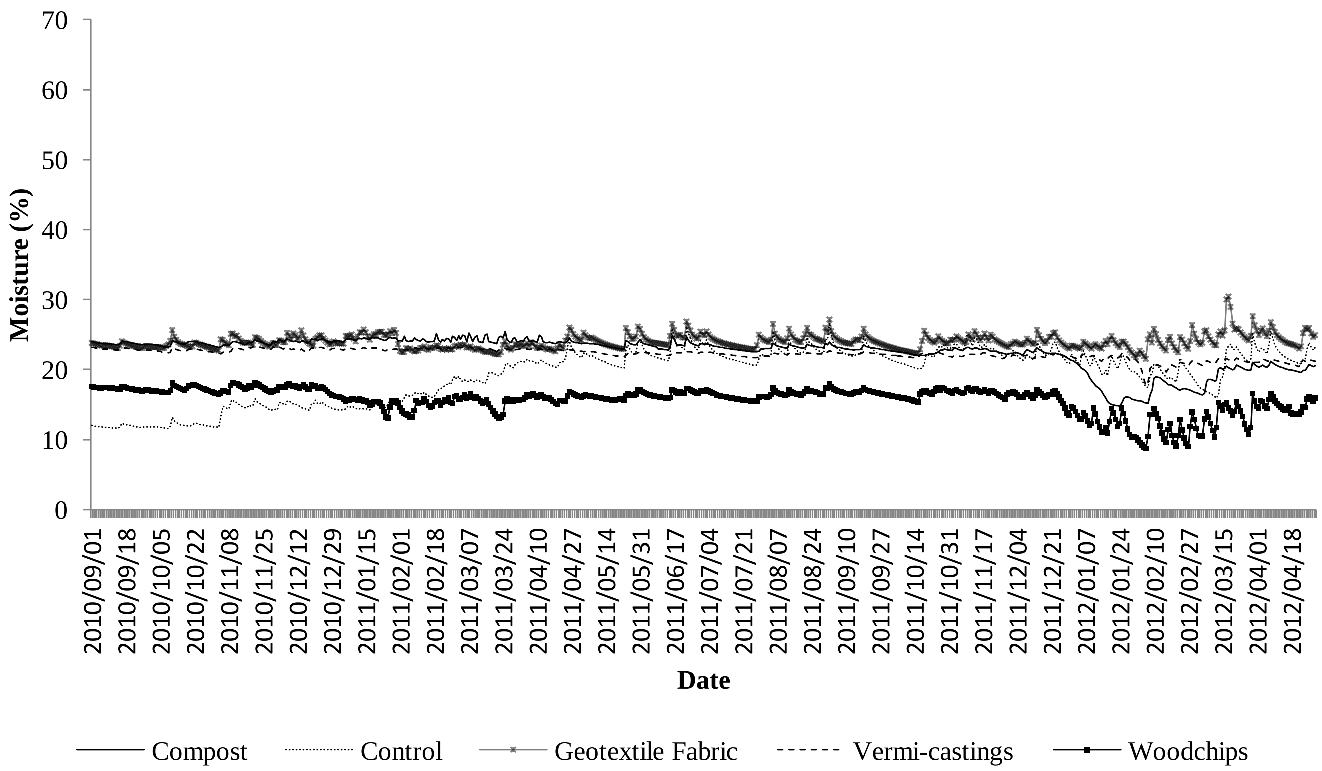

Fig. 23 Average soil water over two seasons (1 Sept 2010 – 30 April 2012) at 40 cm depth of one replicate per treatment in the lighter soil site

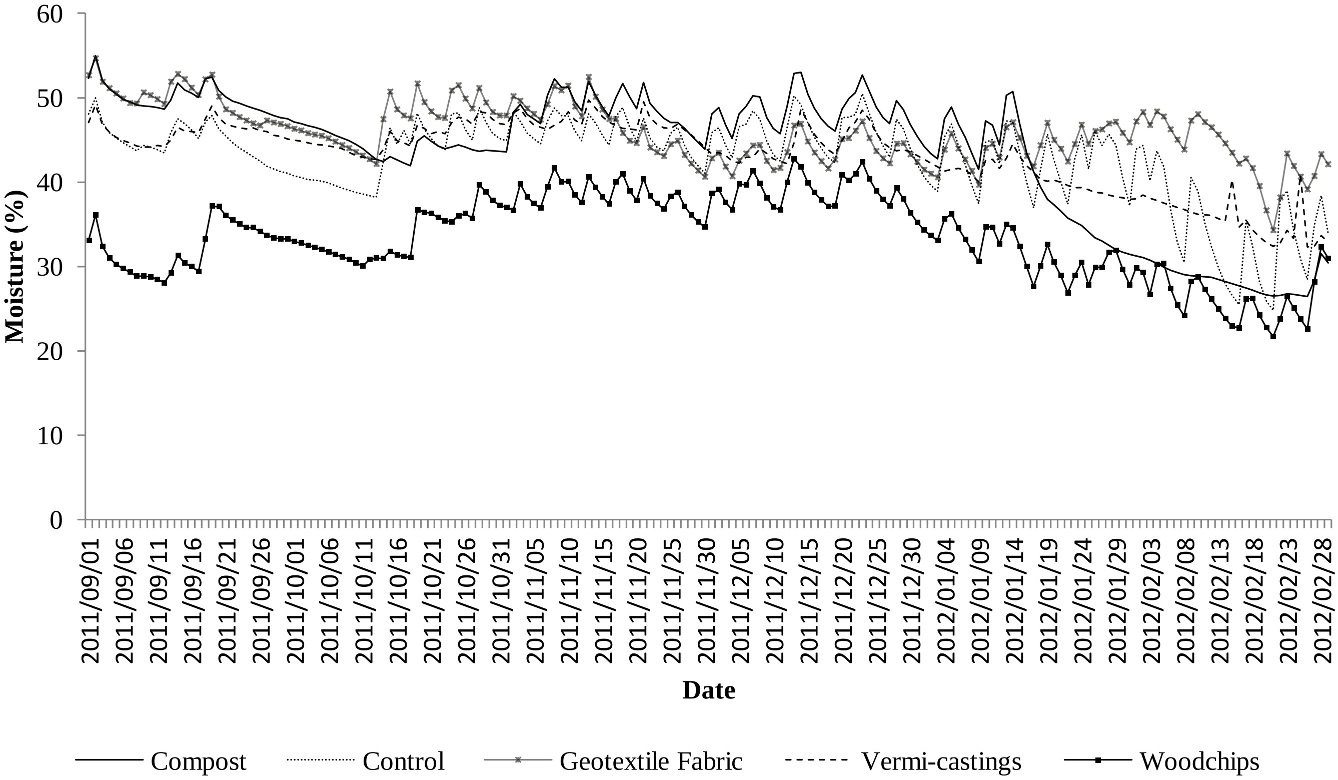

Fig. 24 Average daily soil water at 10 cm depth of the profile of one replicate per treatment in the heavier soil site during the summer months (01 September 2011 – 28 February 2012)

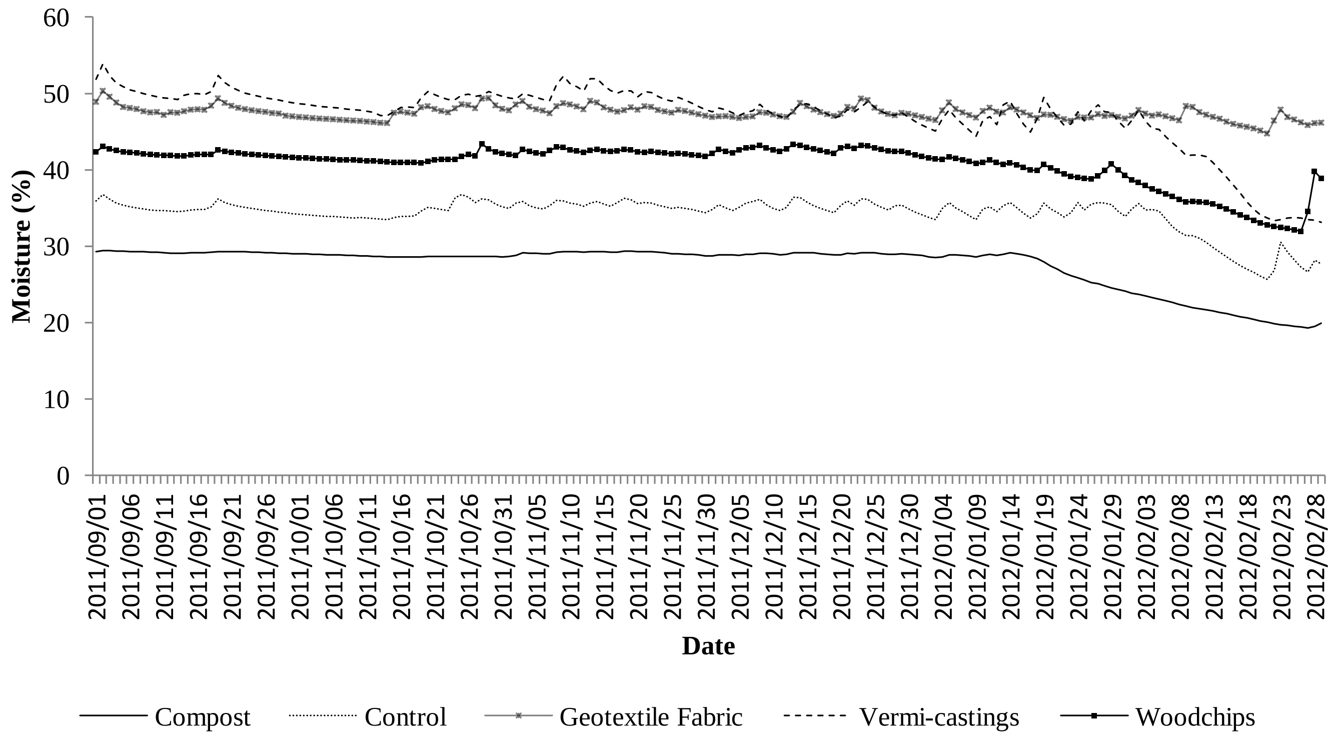

Fig. 25 Average daily soil water at 40 cm depth of the profile of one replicate per treatment in the heavier soil site during the summer months (01 September 2011 – 28 February 2012)

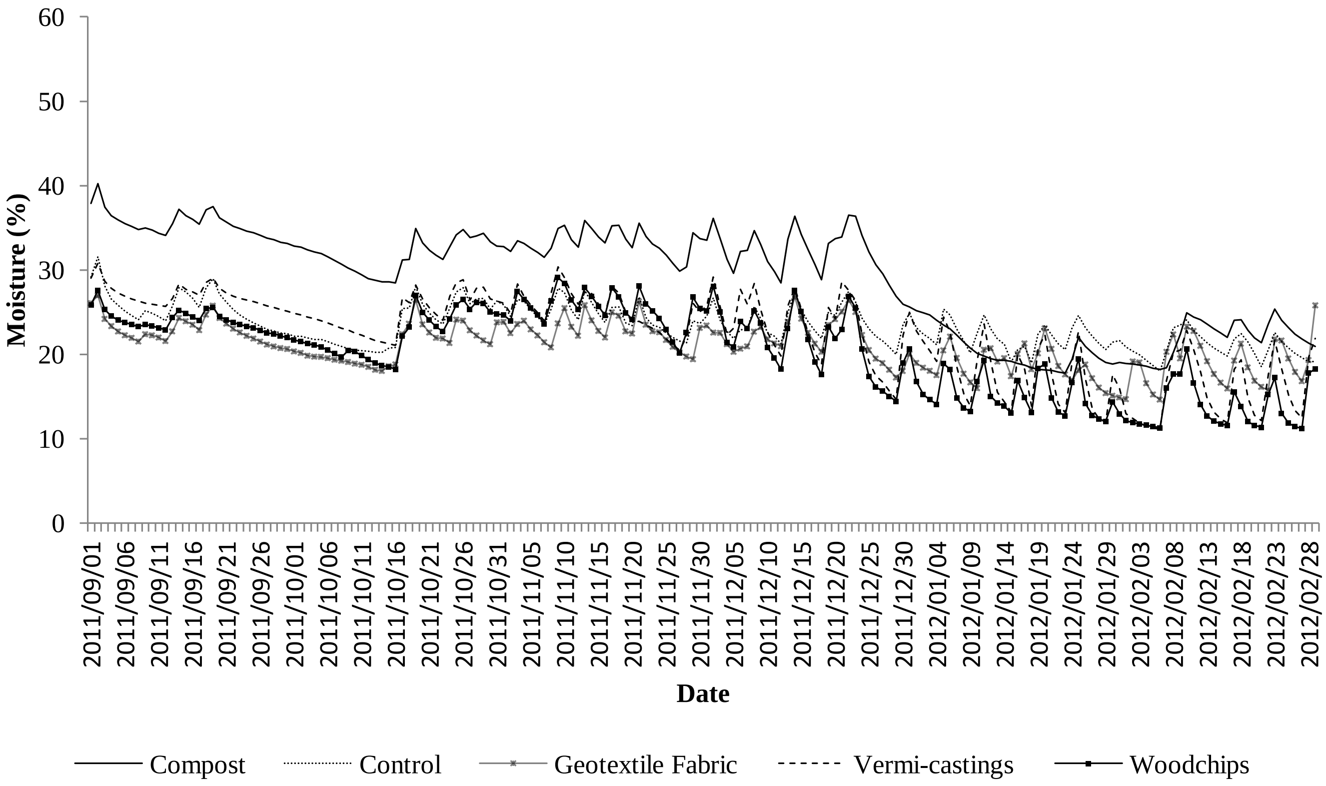

Fig. 26 Average daily soil water at 10 cm depth of the profile of one replicate per treatment in the lighter soil site during the summer months (01 September 2011 – 28 February 2012)

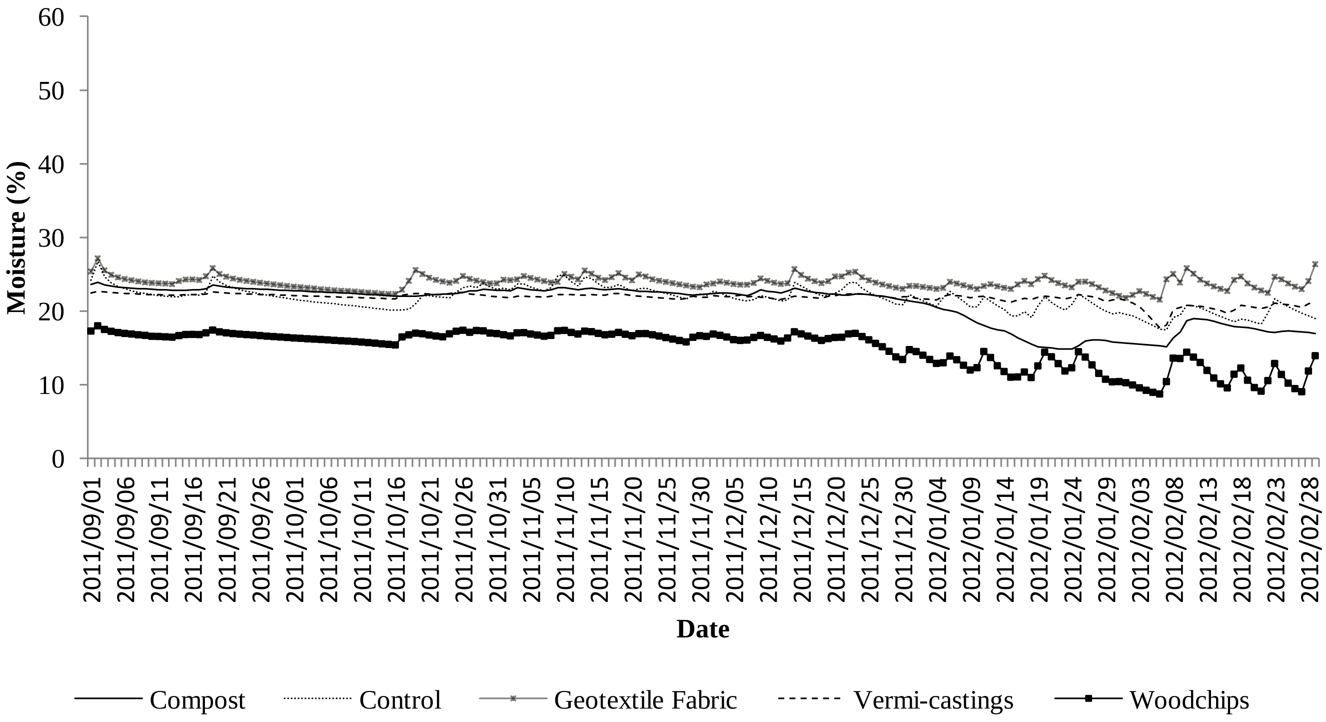

Fig. 27 Average daily soil water at 40 cm depth of the profile of one replicate per treatment in the lighter soil site during the summer months (01 September 2011 – 28 February 2012)

Paper 2

The effect of different mulches on the chemical composition of the root environment of 'Cripps' Pink' apple trees.

Introduction

The organic matter and nutrient status of the soil is of great importance to root growth and must be present in optimal amounts if the roots are to fulfil their fundamental role of nutrient acquisition. With regards to the use of mulches, their primary purpose is not usually aimed at nutrient input into the soil, but aimed at soil water conservation and temperature stabilization. However, organic mulches decompose over time and can release nutrients and increase the organic matter content of the soil, which is however highly dependent on the composition of the mulching material (Wolstenholme et al. 1996). The nutrient status is particularly influenced by soil water status (Giulivo 1990), which is in turn influenced by the degree to which the soil is covered, the type of covering, as well as, the soil’s water holding capacity. Mulches therefore have a secondary effect on the soil nutrients status (Giulivo 1990). However, organic mulches can also contribute directly to the nutrient status due to leaching of minerals from the mulching material itself, decomposition and incorporation of organic matter into the soil (Wolstenholme et al. 1996).

In addition, microorganism populations involved in the mineralization of essential plant nutrients, such as nitrogen, carbon, phosphorous, potassium, magnesium, manganese, iron and zink, into plant available forms, increase under organic mulches, thus making nutrients more available to the plant for uptake (Lakatos et al. 2001). Due to the organic nature and decomposition of the materials, organic mulches are very successful in maintaining a high organic matter content in the upper centimetres of the soil profile, contributing greatly to the soil structure and increasing the cation exchange capacity of the soil (Haynes 1980; Giulivo 1990; Wolstenholme et al. 1996). With an increase in the cation exchange capacity of the soil, fewer cations are leached and therefore, more nutrients are available for uptake by the roots (Haynes 1980).

All soil properties which are important for root growth are closely linked to each other, and soil organic matter content and nutrient availability is no different. If mulching does not directly affect one of these properties, it is bound to have a secondary effect, as is often the case with soil chemistry.

This study was proposed due to insufficient information on the effect of mulches on the chemical properties of the root environment of commercial, perennial crops. As a result of the changes in the physical properties, including, soil temperature and water, it is hypothesised that the chemical properties of the soil will be changed and improved, and an increase in cation exchange capacity will be observed, particularly when applying organic mulches. It is also expected that those mulches containing mineral nutrients will increase soil fertility through leaching of minerals from the mulch.

Materials and Methods

Trial Layout

The trail was carried out at Lourensford Estate, Somerset West, South Africa (-34° 2' 31.29", +18° 55' 16.20") and commenced in October 2008 (Kotze et al. 2012). The trial consisted of two 'Cripps' Pink' apple orchards planted in 1998 on M793 rootstocks on two different soil types. One site was on a heavier soil (Clovelly) and the other, an adjacent orchard, on a lighter soil (Tukulu).

The trial layout was a randomized complete block design with 5 treatments, 6 blocks, repeated on the 2 sites. Two buffer trees were added between plots to differentiate clearly between each plot. Each plot comprised four trees.

Of the five treatments, three were mulches consisting of organic materials, one of an inorganic material and the remaining one was the control, with no mulch. The organic mulches were as follows: wood chips containing no initial significant nutrient levels and originating from various tree species (excluding pine as it is known to leach allelochemicals); compost, where the nutrient levels were determined and vermi-castings (also with determined nutrient composition) with wood chips placed on top to prevent loss of the castings due to rain or wind. The inorganic mulch was a black polytex PT110 woven geotextile fabric that allowed water and nutrients to penetrate the soil, but contained no nutrient levels itself. The control treatment was not mulched and was under clean cultivation, where weeds were controlled according to farm management.

Normal commercial practises were followed regarding orchard management, apart from the irrigation. In January 2011 every second 42 ℓ h^{-1} micro-jet was replaced with a 20 ℓ h^{-1} micro-jet, reducing the deliverance of water due to suspected over irrigation, which became evident from historical data (Kotze et al. 2012). In October 2011 it was decided to further reduce irrigation, based on data acquired from FruitLook satellites, which was only available from 2011 and illustrated a lack of evapotranspiration deficit in both sites (fruitlook.co.za) (data in Paper 1), and thus the deliverance was further reduced by replacing every 42 ℓ h^{-1} micro-jet in the trial with 20 ℓ h^{-1} micro-jet. Evapotranspiration deficit is a measure of plant water stress. Although under normal crop production condition, plant water stress is not usually favourable, due to the nature of the trial and the use of mulching which essentially is a water conservation tool, a certain amount of water stress was require in order to receive results with regard to the mulches. The change in irrigation volumes, however, did not result in water reductions to the extent that would inflict stress on the control plots. The only spikes in evapotranspiration deficit were noted in times of heat waves where ambient temperatures reached upper thirties. The irrigation scheduling was maintained by the farm manager at two hours, three times per week, however irregularities in the irrigation scheduling were found during visits to the sites on various occasions.

Application of Mulches

Organic mulches were reapplied every year from trial commencement in October (2009 – 2011) to maintain a thickness of approximately 5cm on the soil surface. The inorganic mulch treatment, black polytex PT110 woven geotextile fabric, remained from the commencement of the trial.

A total of 90 ℓ of compost and woodchips respectively were evenly dispersed over their respective treatments per block during each reapplication. A total of 60 ℓ of vermi-castings, topped with 30 ℓ of woodchips, were evenly dispersed per block for the vermi-castings treatment.

Soil Mineral Analysis

Mineral analyses of the organic mulches were performed every year in order to determine their mineral composition. The source of the materials remained the same each year. At application, the woodchips mulch contained insignificant nutrient levels at application and therefore was not analyzed. The compost and vermi-castings mulches, however, did contain significant nutrient levels and were therefore analyzed each time the mulch was applied. After each season (April) all three of the organic mulches, including the woodchips mulch, were analyzed due to the changes of the mineral nature of the mulches over time.

Noticeable changes in soil mineral nutrition is relatively slow and thus analyses were only required every two to three years. Soil samples were taken prior to the trial setup from four replicates per site in October 2008 (Kotze et al. 2012). Only four replicate samples were taken due to financial constraints of the project. Two subsamples were taken to make a composite sample from each plot at 0 – 10 cm, 10 – 30 cm and 30 – 50 cm depths. Micro and macro elements, as well as pH, were analyzed in the 0 – 10cm layer, and only macro elements and pH were analyzed in the 10 – 30 cm and 30 – 50 cm layers.

The following soil mineral analysis was done in 2010 (Kotze et al. 2012). Six replicate samples were taken per site in October 2010 from each treatment. Two subsamples were taken to make a composite sample from each plot at 0 – 10 cm and 10 – 30 cm depths. Micro and macro elements, as well as pH, were analyzed in the 0 – 10cm layer, and only macro elements and pH were analyzed in the 10 – 30 cm layer.

The following soil mineral analysis was done in 2012. Six replicate samples were taken per site in May 2012 per treatment. Two subsamples were taken to make a composite sample from each plot at 0 – 10 cm, 10 – 30 cm and 30 – 50 cm depths. Micro and macro elements, as well as pH, hydrogen ions and cation exchange capacity (CEC) were analyzed in the three respective layers.

All sampling was done using a 5 cm Thomson’s auger. All of the samples taken were analyzed by a commercial laboratory (BemLab Pty Ltd, Strand, South Africa).

Statistical Analysis

All data that was of a statistical nature was analyzed using the Statistical Analysing System (SAS) programme 9.1 (SAS Institute Inc, 2004, Cary, NC). Analyses of variances were analyzed using a General Linear Model (GLM) procedure and standard errors and least square means were calculated for each treatment. Data was considered significant at a 5% significance level and 10% significance level where specified.

Results

Soil Mineral Analyses

Historical soil mineral data from 2010, adapted from Kotze et al. (2012), was used along with data from 2012 for the soil mineral analysis.

The normal value for P in a soil with a pH of between 5.5 and 6.5 and where the Bray II method of extraction was used is 30 mg/kg, and the normal value for K in a loamy soil is 4 – 5% (Kotzé 2001). Both sites, as well as all of the treatments, with the exception of the woodchips and geotextile fabric treatments in the deeper soil layers of the heavier soil site, produced P values considerably higher than that of the norm (Table 1, 3, 5, 7, 9 and 11). The K values in both sites generally fell in the optimal range for the loamy soil, with the exception of the compost and vermi-castings resulting in slightly higher values, particularly in the heavier soil site (Table 1, 3, 5, 7, 9 and 11).

The organic mulches were analyzed before application and after a season of coverage in 2012 for macro- and microelements (Fig. 1 – 4). As newly applied mulches, when comparing the compost and vermi-castings mulches, the vermi-castings mulch had a notably higher percentage of N, P, Ca and Mg, where as the compost mulch had a higher percentage K (Fig. 1). After a season of coverage by the organic materials, in the heavier soil site, significant differences occurred between mulches in the percentage P and Mg where the vermi-castings mulch had the highest percentage, and differed significantly from the compost and woodchips mulches. As newly applied mulches, between the compost and vermi-castings mulches, the vermi-castings mulch had notably higher Mn, Copper (Cu) and Zn contents, where as the compost mulch had higher Sodium (Na) and Fe contents (Fig. 2). The vermi-castings mulch also had a slightly higher Boron (B) content. After a season of coverage by the organic materials in the heavier soil site, there was a general decline in nutrient levels and significant differences occurred between mulches in the Cu, Zn, B and Fe contents where the vermi-castings mulch had the highest contents and differed significantly from the compost and woodchips mulches with regards to the Cu and Zn contents, and only from the woodchips mulch with regards to the B and Fe contents.

After a season of coverage by the organic materials in the lighter soil site significant differences occurred between mulches in the percentage N, P, Ca and Mg where the vermi-castings mulch had the highest percentage, and differed significantly from the woodchips mulch (Fig. 3). The compost mulch did not differ significantly from the vermi-castings and woodchips mulches with regards to the percentage P and Mg, but did differ significantly from the woodchips mulch with regards to the percentage N and Ca. Significant differences also occurred between mulches in the Mn, Cu, Na and Fe contents where the vermi-castings mulch had the highest contents and differed significantly from the compost and woodchips mulches with regards to the Mn and Cu contents, and only from the woodchips mulch with regards to the Na and Fe contents (Fig. 4).

In both sites only certain of the macro- and micronutrients are displayed over time for the 0 – 10 cm soil layer, and only certain of the macronutrients for the 10 – 30 cm and 30 – 50 cm soil layers, due to the availability of historical data from 2010, adapted from Kotze et al. (2012) (Fig. 5 – 10). The aim of these figures is only to present an indication of the increases and trends that occurred from 2010 to 2012, and not as to comment on the amount of nutrients in the soils. Comparisons between treatments regarding amount of nutrients in the soils is addressed in Tables 1 to 12.

0 – 10 cm

In the top 10 cm of the heavier soil site, certain of the macronutrients increased and others remained relatively constant over the duration of the trial (Fig. 5). The percentage C increased marginally over all the treatments from 2010 to 2012, ranging from a 0.45% increase in the woodchips mulch, to a 2.04% increase as a result of the geotextile fabric mulch. Increases in percentage Ca where observed in all of the treatments, except the geotextile fabric treatment which remained constant from 2010 to 2012. The greatest increase in percentage Ca over time was noted in the woodchips treatment with a 9.26% increase, as compared to the compost (1.03%), control (2.30%) and vermi-castings (2.31%) treatments. Marginal increases in percentage Mg were observed over time in the compost, control and geotextile fabric treatments, increasing less than 1% from 2010 to 2012. The vermi-castings and woodchips treatments, however, had slightly greater increases in percentage Mg, with increases of 2.89% and 1.75% respectively. The percentage K remained relatively constant over all of the treatments from 2010 to 2012. Greater changes in P content over time were noted compared to the other macronutrients. In both 2010 and 2012 the vermi-castings treatment exceeded the other treatments by over 100 mg/kg. The compost, control, geotextile fabric and woodchips treatments increased between 25 mg/kg (woodchips treatment) and 58 mg/kg (compost treatment) from 2010 to 2012. The vermi-castings treatment, however, increased considerably by 95.92 mg/kg.

The micronutrients generally increased over the commencement of the trial in the heavier soil site at the 0 – 10 cm depth (Fig. 6). The woodchips treatment produced the greatest increase in Cu content, increasing by 2.12 mg/kg from 2010 to 2012. The compost, geotextile fabric and vermi-castings treatments increased marginally by between 1.16 mg/kg and 1.72 mg/kg. The control treatment remained relatively constant with regard to Cu levels from 2010 to 2012. Greater changes in Zn contents were noted over the duration of the trial. The organic mulches elevated Zn levels in 2012 more than the other treatments, with the vermi-castings treatment surpassing the control treatment by 11.68 mg/kg. Zn levels in the vermi-castings, compost and woodchips treatments showed the greatest increases from 2010 to 2012, increasing by 9.08 mg/kg, 8.07 mg/kg and 7.21 mg/kg, as compared to the geotextile fabric and control treatments which only increased by 2.30 mg/kg and 2.32 mg/kg respectively. Considerable changes were also observed in Mn content from 2010 to 2012, with the same trend being observed as for Zn contents. Once again Mn increased in the organic mulches substantially more than the other treatments in 2012, with the vermi-castings treatment having 6.1 mg/kg more Mn than the control treatment. The B content remained relatively constant in all of the treatments from 2010 to 2012, with the greatest increases observed in the vermi-castings and compost treatments. NoTable changes in Fe content, however, occurred from 2010 to 2012 in all the treatments.

The mineral analysis in the heavier soil site in the 0 – 10 cm layer of the soil profile showed significant differences between treatments in the pH analysis ($P = 0.0672$), all of the macronutrients (P ($P = 0.0003$), N ($P = 0.936$), Na^+ ($P = 0.0489$), K^+ ($P = 0.0077$), Ca^+ ($P = 0.0163$), Mg^+ ($P = <0.0001$)), some micronutrients (Zn content ($P = 0.0013$), Mn content ($P = 0.0054$) and B content ($P = 0.0371$)) and the cation exchange capacity analysis ($P = 0.0275$) (Table 1 and 2).

With regards to the pH analysis in the heavier soil site, the vermi-castings treatment, followed by the compost treatment had the highest pH values and were the most neutral of the treatments (pH = 6) (Table 1). These treatments differed significantly from the geotextile fabric treatment, which had the most acidic pH (pH = 5.675) ($p < 0.1$). The control and the woodchips treatments, however, did not differ significantly from any of the treatments and had the same pH values (pH = 5.8).

All of the macronutrients differed significantly between treatments (Table 1). The vermi-castings treatment had significantly higher P (P Bray II) content compared to that of the other treatments ($P < 0.05$). No significant differences between the other treatments were found. As expected, the organic mulch treatments had significantly higher percentages N and although there were no significant differences between these mulches, they did differ significantly from the control treatment ($P < 0.1$). The geotextile fabric treatment did not differ significantly from any of the treatments in terms of percentage N. The vermi-castings treatment had the highest K content and differed significantly from the woodchips, control and geotextile fabric treatments ($P < 0.05$). The compost treatment followed the vermi-castings treatment and they did not differ significantly from each other, however, it also did not differ significantly from the woodchips treatment. Significant differences between treatments were found with regards to the Ca content, where the compost treatment had the highest content and differed significantly from the woodchips, geotextile fabric and control treatments, but not from the vermi-castings treatment ($P < 0.1$). With regards to the Mg content, the vermi-castings treatment had the highest content and differed significantly from the other treatments ($P < 0.05$). Following the vermi-castings treatment were the compost and woodchips treatments, where significant differences were found between the compost treatment and the geotextile fabric and control treatments, and not between the woodchips treatment and the latter treatments.

Some of the micronutrients differed significantly between treatments in the top 10 cm of the heavier soil site ($P < 0.05$) (Table 2). With regards to the Na content, the vermi-castings treatment had the highest content and differed significantly from the woodchips, geotextile fabric and control treatments ($P < 0.05$). The compost treatment did not differ significantly from any of the treatments. With regards to the Zn content, the vermi-castings treatment differed significantly from the other treatments and had the highest content. It was followed by the compost treatment which did not differ significantly from the woodchips treatment. The woodchips treatment in turn did not differ significantly from the control and geotextile fabric treatments which had the lowest Zn contents. The Mn and B contents followed similar trends to that of the Zn content.

Significant differences between treatments were found with regards to the CEC of the heavier soil site, with the organic mulches exhibiting the highest levels of exchangeable cations and the control and geotextile treatments having the lowest ($P < 0.05$) (Table 2). The organic mulch treatments had significantly higher CEC and did not differ significantly from each other. They did, however, differ significantly from the control treatment. The geotextile fabric treatment did not differ significantly from any of the treatments.

In the lighter soil site at the 0 – 10 cm depth, certain of the macronutrients increased and others remained relatively constant over the duration of the trial (Fig. 7). The % C increased marginally over all the treatments from 2010 to 2012, with the greatest increase of 3.30% as a result of the compost treatment. Contrary to the heavier soil site, increases in percentage Ca in the lighter soil site where only observed in the geotextile fabric, vermi-castings and woodchips treatments, with the greatest increase of 3.34% in the geotextile fabric treatment. The compost and control treatments, however, decreased marginally in percentage Ca from 2010 to 2012. Increases in % Mg were observed over time in the geotextile fabric, compost, control and woodchips treatments, increasing by 7.47%, 5.58%, 3.32% and 1.00% respectively. The vermi-castings treatment, however, decreased marginally in % Mg. The % K remained relatively constant over all of the treatments from 2010 to 2012. Greater changes in P content over time were noted compared to the other macronutrients. The greatest increases where realized by the compost and geotextile fabric treatments, increasing by 136.75 mg/kg and 136.08 mg/kg respectively. The vermi-castings and woodchips treatments increased by 53.5 mg/kg and 62.58 mg/kg respectively, with the control treatment realizing the smallest increase of 13.58 mg/kg.

The micronutrients generally increased over the duration of the trial in the lighter soil site at the 0 – 10 cm depth (Fig. 8). The geotextile fabric, compost and vermi-castings treatments exhibited the greatest increase in Cu content, increasing by 2.85 mg/kg, 2.75 mg/kg and 2.44 mg/kg respectively from 2010 to 2012. The woodchips treatment increased marginally by 0.79 mg/kg and the control treatment did not show an increase in Cu content. Greater changes in Zn contents were noted over the duration of the trial, with the mulched treatments showing considerably higher Zn levels than the control treatment in 2012. In addition, the mulched treatments exhibited the greatest increases in Zn from 2010 to 2012. The control treatment did not show an increase in Zn content. Considerable changes were also observed in Mn contents from 2010 to 2012, with the mulched treatments having considerably higher Mn levels than the control treatment in 2012, and the vermi-castings treatment surpassing the control treatment by 14.65 mg/kg. The vermi-castings treatment was followed by the geotextile fabric, compost and woodchips treatments. The mulched treatments produced the greatest increases from 2010 to 2012, increasing by between 17.97 mg/kg as a result of the vermi-castings treatment, and 5.66 mg/kg as a result of the woodchips treatment. The control treatment, however, only realized an increase of 3.27 mg/kg. The B content increased marginally over all of the treatments from 2010 to 2012, the greatest increases resulting from the vermi-castings, compost and geotextile fabric treatments. Considerable changes in Fe content, however, occurred from 2010 to 2012 over all of the treatments. The control treatment realized the greatest increase of 57.04 mg/kg, where as the woodchips treatment realized the smallest increase of 15.64 mg/kg.

The mineral analysis in the lighter soil site at the 0 – 10 cm layer of the soil profile showed significant differences between treatments in the % C ($P = 0.0169$) and one micronutrient (Cu content ($P = 0.0079$)) (Table 3 and 4). No significant differences were found in any of the macronutrients (Table 3), or the CEC (Table 4).

With regards to the % C in the lighter soil site, the compost treatment, followed by the vermi-castings treatment, had the highest percentages and did not differ significantly from each other ($P < 0.05$) (Table 3). The compost treatment did, however, differ significantly from the other treatments. The vermi-castings treatment did not differ significantly from the geotextile fabric and woodchips treatments, but did differ significantly from the control treatment. The geotextile fabric, woodchips and control treatments did not differ significantly from each other and had the lowest percentages.

Significant differences between treatments were found with regards to the Cu content in the lighter soil site ($P < 0.05$) (Table 4). The control treatment had a significantly lower Cu content compared to the other treatments, which in turn did not differ significantly from each other.

10 – 30 cm

In the heavier soil site at the 10 – 30 cm depth, as with the 0 – 10 cm soil layer, certain of the macronutrients increased and others remained relatively constant over the duration of the trial (Fig. 9). The % C increased marginally over all the mulched treatments from 2010 to 2012, ranging from a 1.78 % increase as a result of the compost mulch, to a 0.14% increase as a result of the geotextile fabric mulch. There was, however, a decrease in the % C from 2010 to 2012 in the control treatment. Increases in % Ca where observed in all of the treatments from 2010 to 2012. The greatest increase in % Ca over time was noted in the woodchips treatment with a 17.75% increase, where as the compost, control geotextile fabric and vermi-castings treatments increased by between 9.56%, as a result of the geotextile fabric treatment, and

0.918%, as a result of the vermi-castings treatment. The vermi-castings and woodchips treatments, however, produced greater increases in % Mg, with increases of 5.39% and 2.78% respectively. The control treatment, however, decreased in percentage Mg. The % K remained relatively constant over all of the treatments from 2010 to 2012. In both 2010 and 2012 P content in the vermi-castings treatment exceeded the other treatments by over 30 mg/kg. The compost, control, geotextile fabric and woodchips treatments increased between 16 mg/kg (geotextile fabric treatment) and 23.33 mg/kg (compost treatment) from 2010 to 2012. The vermi-castings treatment, however, increased considerably by 63.5 mg/kg.

Similarly to that of the 0 – 10 cm layer of the soil profile, the mineral analysis in the heavier soil site at 10 – 30 cm layer showed significant differences between treatments in the pH analysis ($P = 0.0964$), three of the macronutrients (P ($P = 0.0028$), K^+ ($P = 0.0029$), Mg^+ ($P = 0.0003$)) and some micronutrients (Zn content ($P = 0.0004$), Mn content ($P = 0.0012$) and B content ($P = 0.0695$)) (Table 5 and 6). In contrast to the top 10 cm soil layer, no significantly differences were found in the percentage N, Na^+ and Ca^+ contents and the cation exchange capacity, (Table 5).

With regards to the pH analysis in the heavier soil site, the vermi-castings treatment, followed by the compost treatment had the highest pH values and were the most neutral of all the treatments (pH = 5.8) (Table 5). These pH values were, however, observed to decrease with depth by approximately 0.2 units. These treatments differed significantly from the geotextile fabric treatment, which had the most acidic pH (pH = 5.38) ($P < 0.1$). The control and the woodchips treatments did not differ significantly from any of the other treatments with pH values between 5.48 and 5.65.

Some of the macronutrients differed significantly between treatments in the heavier soil site (Table 5). Corresponding to the 0 – 10 cm soil layer, the vermi-castings treatment had a significantly higher P (P Bray II) content compared to the other treatments ($P < 0.05$). No significant differences between other treatments were found. With regards to the K content, similar to the 0 – 10 cm soil layer, the vermi-castings treatment had the highest content and differed significantly from the woodchips, control and geotextile fabric treatments ($P < 0.05$). The compost treatment followed the vermi-castings treatment and they did not differ significantly from each other, however, it also did not differ significantly from the woodchips treatment. The vermi-castings mulch had significantly higher exchangeable Mg than all the other treatments ($P < 0.05$).

Some of the micronutrients differed significantly between treatments in the heavier soil site (Table 6). As with the 0 – 10 cm soil layer, Zn content in the 10 – 30 cm layer was significantly higher in the vermi-castings treatment compared to the other treatments ($P < 0.05$). It was followed by the compost treatment which did not differ significantly from the woodchips treatment. The woodchips treatment in turn did not differ significantly from the control and geotextile fabric treatments which had the lowest Zn contents. Mn and B contents once again followed similar trends to that of the Zn content. However, where the Zn content showed significant differences between the vermi-castings and compost treatments ($P < 0.05$), the B content showed no significant differences between these treatments ($P < 0.1$); and where the control treatment differed significantly from the compost treatment with regards to the Zn content, the control treatment did not differ significantly from the compost treatment with that of the B content. It was also noted that the woodchips treatment did not differ significantly from any of the treatments with regards to B content.

In the lighter soil site at the 10 – 30 cm depth, as with the 0 – 10 cm soil layer, certain of the macronutrients increased and others remained relatively constant over the commencement of the trial (Fig. 10). The % C increased marginally over all the treatments from 2010 to 2012, with the greatest increase of 3.65% as a result of the compost treatment. Increases in % Ca where observed in the geotextile fabric, vermi-castings and woodchips treatments, with the greatest increase of 2.98% as a result of the woodchips treatment. The compost and control treatments, however, decreased marginally in % Ca from 2010 to 2012. Increases in % Mg were observed over time in all of the treatment, increasing by between 6.46% in the geotextile fabric treatment, and 2.14% in the vermi-castings treatment. The % K remained relatively constant over all of the treatments from 2010 to 2012. Greater changes in P content over time were noted compared to the other macronutrients. The greatest increases where realized by the woodchips and compost treatments, increasing by 61.33 mg/kg and 60.25 mg/kg respectively. The geotextile fabric and vermi-castings treatments increased by 49.08 mg/kg and 15.67 mg/kg respectively, with the control treatment realizing the smallest increase of 4.67 mg/kg.

Similarly to that of the 0 – 10 cm layer of the soil profile, the mineral analysis in the lighter soil site at 10 – 30 cm layer showed significant differences between treatments in the percentage C ($P = 0.0463$) (Table 7). No significant differences were found in any of the macronutrients (Table 7), micronutrients or the CEC (Table 8).

With regards to the % C in the lighter soil site, the compost treatment, followed by the geotextile fabric and vermi-castings treatments, had the highest C contents and did not differ significantly from each other ($P < 0.05$) (Table 7). The compost treatment did, however, differ significantly from control and woodchips treatments which had the lowest % C.

30 – 50 cm

Similarly to that of the 0 – 10 cm and 10 – 30 cm layers of the soil profile, the mineral analysis in the heavier soil site at 30 – 50 cm layer showed significant differences between treatments in the pH analysis ($P = 0.0573$), some macronutrients (P ($P = 0.0154$), N ($P = 0.0917$), K^+ ($P = 0.0016$), Mg^+ ($P = 0.0049$)) and some micronutrients (Zn content ($P = 0.0045$), Mn content ($P = 0.0009$) and B content ($P = 0.077$) (Table 9 and 10).

With regards to the pH analysis in the heavier soil site and corresponding to the above soil layers, the vermi-castings treatment had the highest pH values and was the most neutral of the treatments (pH = 5.7) (Table 9). As observed with the 10 – 30 cm soil layer, the pH values of the treatments tended to decrease with depth. The vermi-castings treatment differed significantly from the geotextile fabric treatment, which had the most acidic pH (pH = 5.28) ($P < 0.1$). In contrast to the above soil layers, however, the woodchips treatment differed significantly from vermi-castings treatment and along with the geotextile fabric treatment, they had most acidic pH values. The compost and control treatments did not differ significantly from any of the treatments.

Some of the macronutrients differed significantly between treatments in the heavier soil site (Table 9). Corresponding to the above soil layer, the vermi-castings treatment had a significantly higher P (P Bray II) content compared to the other treatments ($P < 0.05$). No significant differences between the other treatments were found. In contrast, however, to the 10 – 30 cm soil layer, but corresponding to the 0 – 10 cm soil layer, significant differences were found in the % N ($P < 0.1$). The woodchips treatment had the highest percentage and differed significantly from the control treatment. The compost, vermi-castings and geotextile fabric treatments did not differ significantly from any of the treatments. With regards to the exchangeable K content, the vermi-castings and compost treatments had the highest content and differed significantly from the other treatments ($P < 0.05$). No significant differences were found between any of the other treatments. Significant differences between treatments were found with regards to the Mg content, where the vermi-castings treatment had the highest content and differed significantly from the other treatments ($P < 0.05$). No significant differences were found between any of the other treatments.

Some of the micronutrients differed significantly between treatments in the heavier soil site (Table 10). As with to the above soil layers, the vermi-castings treatment had a significantly higher Zn content compared to the other treatments ($P < 0.05$). In contrast, however, no significant differences were found between the other treatments. With regards to the Mn content, the vermi-castings treatment had a significantly higher content compared to the other treatments ($P < 0.05$). The compost treatment followed the vermi-castings treatment and differed significantly from the control treatment, which had the lowest Mn content. The woodchips treatment and geotextile fabric treatments did not differ significantly from each other, and the compost and control treatments. The vermi-castings treatment also had a significantly higher B content ($P < 0.1$), however, in contrast to the Mn contents; it did not differ significantly from the compost and woodchips treatments. Significant differences were found between the vermi-castings treatment and the geotextile fabric and control treatments. The compost and woodchips treatments did not differ significantly from any of the treatments.

In contrast to that of the 0 – 10 cm and 10 – 30 cm layers of the soil profile, the mineral analysis in the lighter soil site at the 30 – 50 cm soil layer showed no significant differences between treatments in any of the mineral analyses done (Table 11 and 12).

Discussion

Soil Mineral Analysis

In the heavier soil site, at the three analyzed depths, the geotextile fabric treatment had the lowest pH (5.7 – 5.3) and the vermi-castings and compost treatments had the highest (6.0 – 5.7 and 6.0 – 5.6 respectively). Plants generally prefer slightly acidic soil solutions, ranging between 5.5 and 6.5 (Taiz and Zeiger 2010), and apple trees are no exception to this, however, they can tolerate soils that are slightly more neutral. As pointed out by Haynes (1980), unfavourable acidic conditions amount to leaching of exchangeable bases and certain nutrient toxicities such as Mn. With the leaching of exchangeable bases and toxicities of certain nutrients, the soil could lead to undesirable conditions in this regard, not only for root growth, development and functioning, but also biological properties of the soil (Haynes, 1980). The vermi-castings and compost treatments differed significantly from the geotextile fabric treatment on the 10% significance level and this may be attributed to the higher pH of the mulching materials themselves. Due to the higher silt content of the heavier soil site, there is a higher surface area for the binding of cations to silt and clay particles of the soil, therefore cations that are leached from the mulching materials on top of the soil surface are held in the soil, below the soil surface, thus resulting in a higher pH.

In the lighter soil site, however, none of the treatments differed significantly from each other and the pH values ranged from 5.63 to 6.25. Both sites range at optimum pH levels for apple tree roots and nutrient availability, and therefore no imbalances in nutrients should occur as a result.

In the heavier soil site, the vermi-castings treatment resulted in significantly higher percentage N, K, and Mg, and P, Zn, Mn, and B contents compared to the other treatments. This is expected as organic mulches are known to decompose over time and can release nutrients into the soil (Wolstenholme et al. 1996). It also resulted in significantly higher CEC and exchangeable cations such as Na^+, K^+ and Mg^+, with the exception of some of these nutrients and exchangeable ions at deeper soil layers. With regards to many of the above mentioned nutrients and exchangeable ions, the compost treatment never differed from the vermi-castings treatment. In the lighter soil site, the compost treatment resulted in a significantly higher percentage C to a depth of 30 cm in the soil, but it was not significantly different from the vermi-castings treatment. These results provide some proof that organic mulches have the ability to contribute to the soil's nutrient status after four years of application and confirm the remarks from Wolstenholme et al. (1996). A possible reason for the organic mulches resulting in no significant differences in the lighter soil site is that the nutrients are more easily leached out of the profile, especially under conditions of over irrigation, and therefore any significant nutrient additions that the organic mulches make to the soil are leached away. This is evident in the low CEC of the lighter soil site, dropping to 4.335 cmol(+)/kg, compared to that of the heavier soil site, reaching 12.74 cmol(+)/kg. The higher silt component of the heavier silt loam site therefore contributed to a higher adsorption of cations and thus contrasting results occurred between the two sites.

The significantly higher CEC achieved by the organic mulched treatments, compared to the inorganic mulched and the control treatments, in the 0 – 10 cm soil layer of the heavier soil site, may have been due to an increase in organic matter near the soil surface, which is supported by the findings of Haynes (1980) and Wolstenholme et al. (1996). These findings are in agreement with those of Lang et al. (2001) who investigated the use of mulching to increase apple fruit storage. They concluded that the CEC was higher in soil mulched with organic materials. Although this is not entirely confirmed in this site by the % C which was used to quantify organic matter, further investigation into organic matter content need to be done as future research, in order to support this theory.

Wolstenholme et al. (1996) reported that P, Ca and B levels in soils increased as a result of organic mulches, however is greatly dependent on the mulching material used. In the heavier soil site, at both the 0 – 10 cm and 10 – 30 cm soil layers, the vermi-castings treatment was found to increase the soil's P content the most, increasing by 95.92 mg/kg in 2010 and 63.5 mg/kg in 2012. It was also significantly higher than the other treatments at all three analyzed depths in 2012, ranging from 254.25 mg/kg to 103.5 mg/kg, decreasing with depth. This may be attributed to the higher P content found in the newly applied mulching material which decreased considerably after a season of cover. The compost treatment also resulted in significant increases in P from 2010 to 2012 but not as much as in the vermi-castings treatment, increasing by 58.17 mg/kg in the 0 – 10 cm soil layer and 23.33 mg/kg in the 10 – 30 cm soil layer. According to Kotzé (2001), the normal value for P in a soil with a pH found in both sites, where the Bray II method of extraction was used, is 30 mg/kg. Both sites, as well as all of the treatments, with the exception of the woodchips and geotextile fabric treatments in the deeper soil layers of the heavier soil site, produced P values considerably higher than that of the norm. These results can have a significant effect on soil biota, particularly mycorrhizea colonization of the roots (Taiz and Zeiger 2010) (discussed in Paper 3), as well as, fruit quality (discussed in Paper 4). Sharples (1980) reported that excess phosphorous reduced the eating quality of apples and pears as reduced aroma and sweetness, as well as, late ripening where associated with excess phosphorous. In addition, Jakobsen (1979) reported that too much phosphorous may result in calcium phosphate precipitation at the root surface and cause calcium deficiency, which in turn results in quality deterioration. Due to the excess P found in all of the treatments, including the control treatment, in both sites, it may be as a result of the fertilizer program that was used (discussed in Paper 4).

At both the 0 – 10 cm and 10 – 30 cm soil layers, the woodchips treatment was found to increase the most with regards to percentage Ca in the soil, increasing by 9.26 mg/kg in 2010 and 17.75 mg/kg in 2012. However, with the exception of the vermi-castings treatment in the 30 – 50 cm soil layer, none of the treatments differed significantly from each other in 2012.

Due to the immobile nature of Ca in the soil (Taiz and Zeiger 2010), Ca in the woodchips would unlikely to have leached into the soil and explain the higher Ca levels found as a result of the woodchips treatment. However, Lang et al. (2001) attributed increased levels of the soil minerals found in there trials, such as these, to an increase in nutrient cycling as a result of mulches.

The vermi-castings treatment realized the highest B content in all three of the analysed soil layers in the heavier soil site and differed significantly from the control and geotextile fabric treatment. Marginal increases from 2010 to 2012 occurred across the treatments with regard to B content. It is possible that the vermi-castings mulching material directly contributed to the higher percentage P and B content, as it was found to obtain significantly higher levels with regard to these nutrients.

In contrast to the heavier soil site, the compost treatment in the 0 – 10 cm layer of the lighter soil site realised the greatest increase in P content from 2010 to 2012, increasing by 136.75 mg/kg. However, it was marginally surpassed by the woodchips treatment in the 10 – 30 cm layer, which realized an increase of 61.33 mg/kg. The increase in P in the woodchips treatment is confirmed by a study done by St. Laurent et al. (2008) on apple trees, where bark mulch was used, as well as a study by Merwin et al. (1995) on young apple orchards where woodchips mulch was used. In both studies increases in P were found. There were, however, no significant differences between treatments in 2012 with regards to the P contents, or percentage Ca and B contents in any of the three analyzed depths. In addition to some of these nutrients originating from the mulching materials, the findings of both sites support reports from Wolstenholme et al. (1996) that these nutrients increase as a result of organic mulches. These nutrients therefore increase as a result of addition by the actual organic mulching material, an increase in nutrient cycling as a result of the increase in organic material from the organic materials (Haynes 1980; Wolstenholme et al. 1996; Lang et al. 2001), and thus increased availability of the nutrients to the plant.

In the lighter soil site, at the 0 – 10 cm and 10 – 30 cm soil layers, the compost and vermi-castings treatments were found to be significantly higher in percentage C than the control treatment. The percentage C in the compost treatment was also significantly higher than the geotextile fabric and woodchips treatments. No significant differences were found in the deeper soil layer. Haynes (1980) reported that the decomposition of organic ground covers resulted in an increase in soil organic matter in the top soil layers, which consequently increased the C content. This was observed in compost and vermi-castings treatments, but not in woodchips treatment. A possible explanation for this is the partial decomposed nature of the compost and vermi-casting's materials prior to mulch application. The rate of decomposition and incorporation of these mulches into the soil is more rapid than that of the woodchips treatment (Handreck and Black 1994). The actual woodchips that make up this mulch are also larger in size, less dense in volume and comprises only woody materials (containing cellulose and lignin which degrade and decompose much slower), versus the vermi-castings and compost, which results in slower decomposition.

During the decomposition process, nitrogen is released in the form of ammonium and is subject to nitrification, thus making it more prone to leaching (Maynard, 1989; Taiz and Zeiger, 2010). According to Maynard (1989) nitrification of ammonium to nitrate does not pose a huge problem with regard to nitrogen entering the soil from organic matter, as it is released very slowly, and the author suggests that organic mulches with low carbon:nitrogen (C:N) (< 100:1) ratios reduce the need for the application of inorganic nitrogen fertilizers. All of the mulches used in this trial contained sufficient N compared to C (between 2.29% and 1.59%) to keep the C:N low (< 100). It was also found, in the heavier soil site, that the percentage N was significantly higher in the organic mulches compared to that of the control and geotextile treatments.

In the heavier soil site the vermi-castings and woodchips treatments had significantly higher percentage Mg in the top 10 cm of the profile compared to the other treatments. The vermi-castings treatment remained significantly higher than the other treatments with depth, however, the woodchips treatment did not. These findings correspond with the findings of Lang et al. (2001) who concluded that mulching increased Mg concentrations in the upper soil profile. Although not all of the mulches in this trial showed significantly higher Mg percentage in the soil, the un-mulched surface consistently showed the lowest Mg percentage.

Conclusion

The effects of mulching are dependent on the type of soil that is being covered and the outcomes that are intended to be achieved. The vermi-castings mulch was superior in increasing nutrient levels in the soil of the heavier soil site. In contrast, no treatment ameliorated the nutrient status of the lighter soil, with exception the increase in percentage C resulting from the compost and vermi-castings treatments. The significantly higher levels of nutrients (macro and micro) (P, N, K, Mg, Zn, Mn, B) and exchangeable cations (Na^+, K^+, Ca^+, Mg^+) achieved by the vermi-castings treatment in the heavier soil site were largely due to the notably higher nutrients found in the mulching material prior to application. Not all of these increases were beneficial, such as the excess P levels in the soil, which were not only found in the vermi-castings treatment and therefore the negative effect of excess P in the soil was not an effect of the mulch. In addition to directly affecting the nutrient status, the vermi-castings treatment retained higher/intermediate soil water and temperatures in the soil which allows these nutrients to become more available to the plant (data in Paper 1).

Due to the consistency of the organic mulching materials producing higher nutrient levels in the soil over time, the addition of organic matter to the soil is largely to answer for this. The effect can therefore be direct, in terms of nutrient addition by the increased organic matter over time, or indirect, in terms of soil environment amelioration by the organic matter, resulting in increased nutrient levels.

The lack of nutrient status improvements as a result of mulching in the lighter soil site may be due to the nature of the lighter textured soil, allowing for more leaching of the nutrients, especially under conditions of over irrigation. This was supported by the lack of change in physical properties of the soil in the lighter soil site as a result of mulching (data Paper 1). The increase in percentage C after application of organic mulches in the lighter soil site is confirms previous reports stating that organic mulched increase organic matter near the soil surface.

On a practical level, the cost of organic mulches and the actual contribution of nutrients towards the commercial fertiliser program need to be calculated to determine the feasibility of adding a mulch with a nutrient contribution, i.e. compost, versus an organic mulch without its own nutrient status, i.e. wood chips, to reduce/supplement fertiliser inputs.

In this trial, the influence of the soil type on the effect of different mulches on soil chemistry was very prominent. Organic mulches were able to ameliorate both soils, but in the heavier soil type it manifested as an increase in the nutrient status of the soil, whereas in the sandier soil type, the main change was a change in % carbon.

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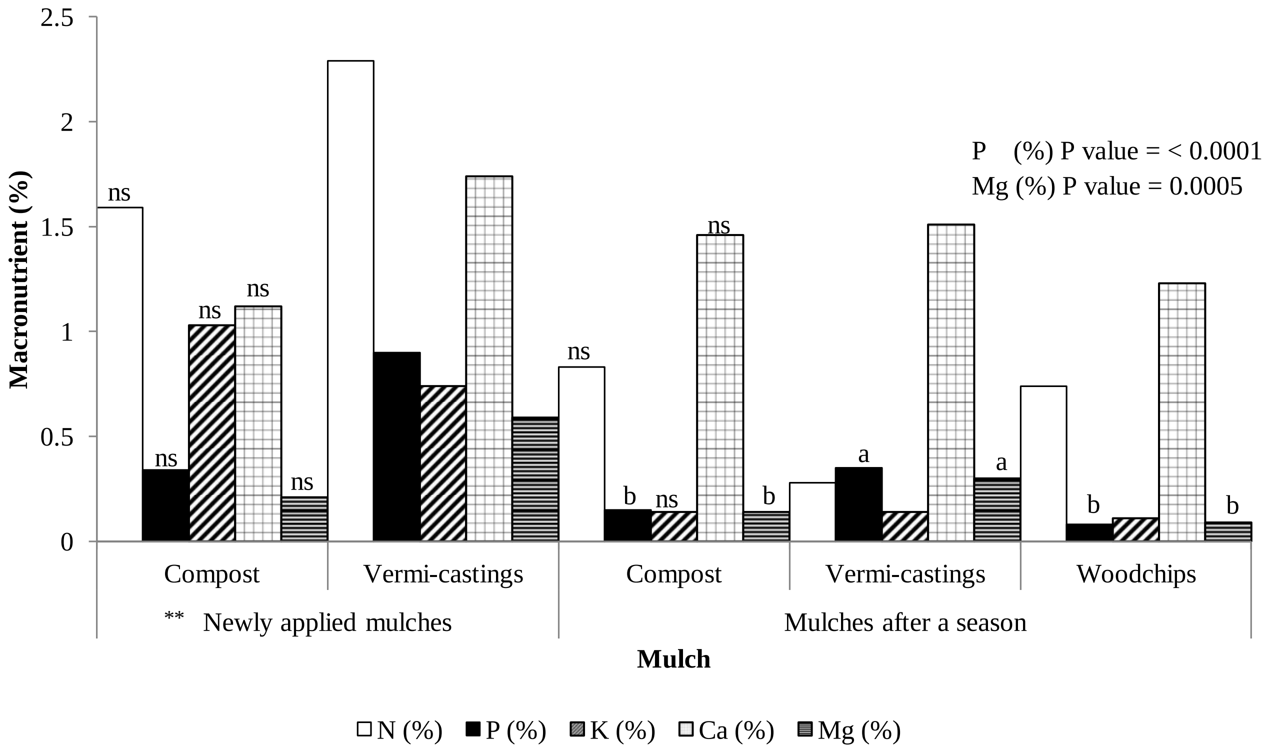

Fig. 1 Macronutrient mulch analysis of the newly applied mulches and the mulches after a season in 2012, at the heavier soil site

* Means with different small letters differed significantly at P<0.05. Means with "ns" were not significantly different.

** The woodchips mulch was not analyzed as a newly applied mulch due to the undecomposed nature of the material.

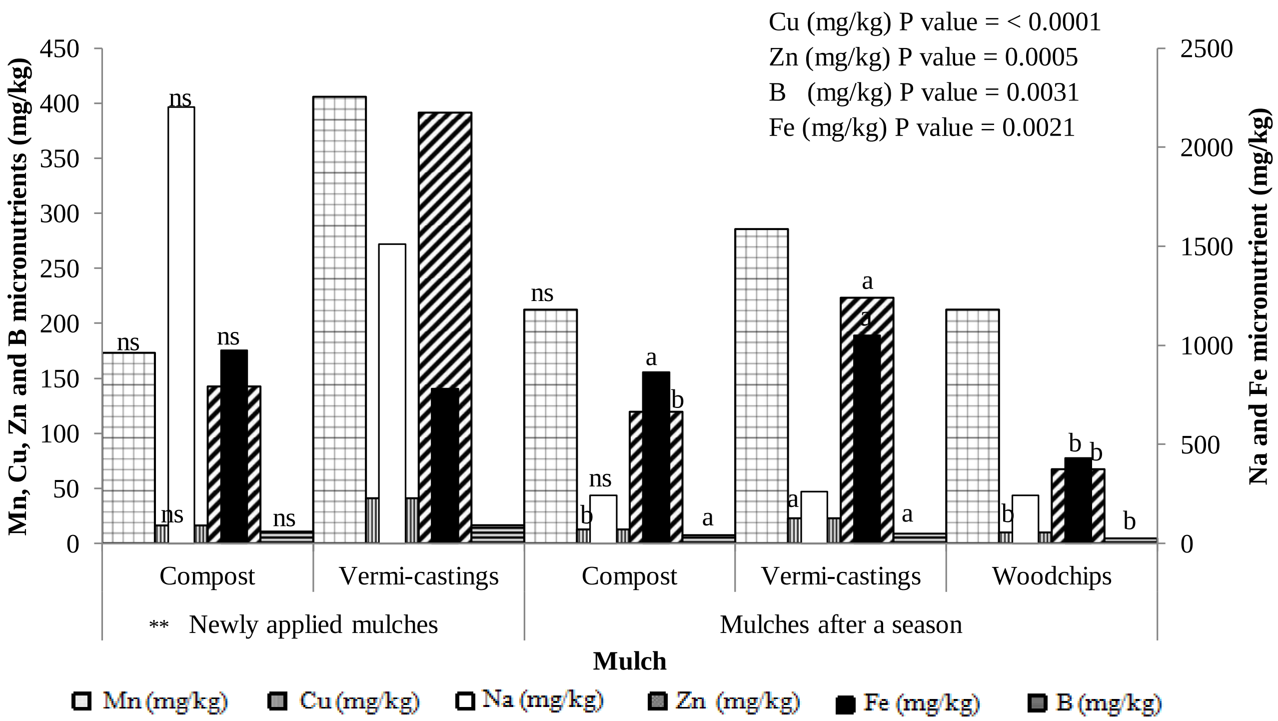

Fig. 2 Micronutrient mulch analysis of the newly applied mulches and the mulches after a season in 2012, at the heavier soil site

* Means with different small letters differed significantly at P<0.05. Means with "ns" were not significantly different

** The woodchips mulch was not analyzed as a newly applied mulch due to the undecomposed nature of the material.

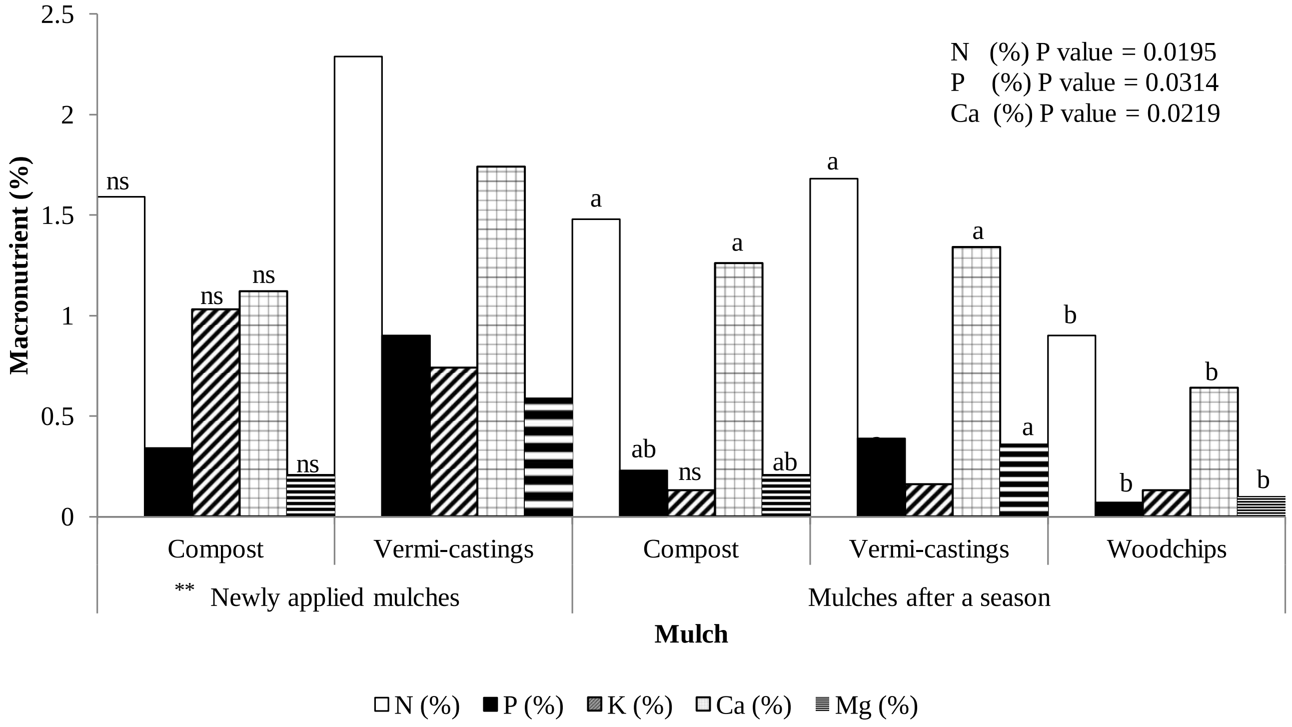

Fig. 3 Macronutrient mulch analysis of the newly applied mulches and the mulches after a season in 2012, at the lighter soil site

* Means with different small letters differed significantly at P<0.05. Means with "ns" were not significantly different.

** The woodchips mulch was not analyzed as a newly applied mulch due to the undecomposed nature of the material.

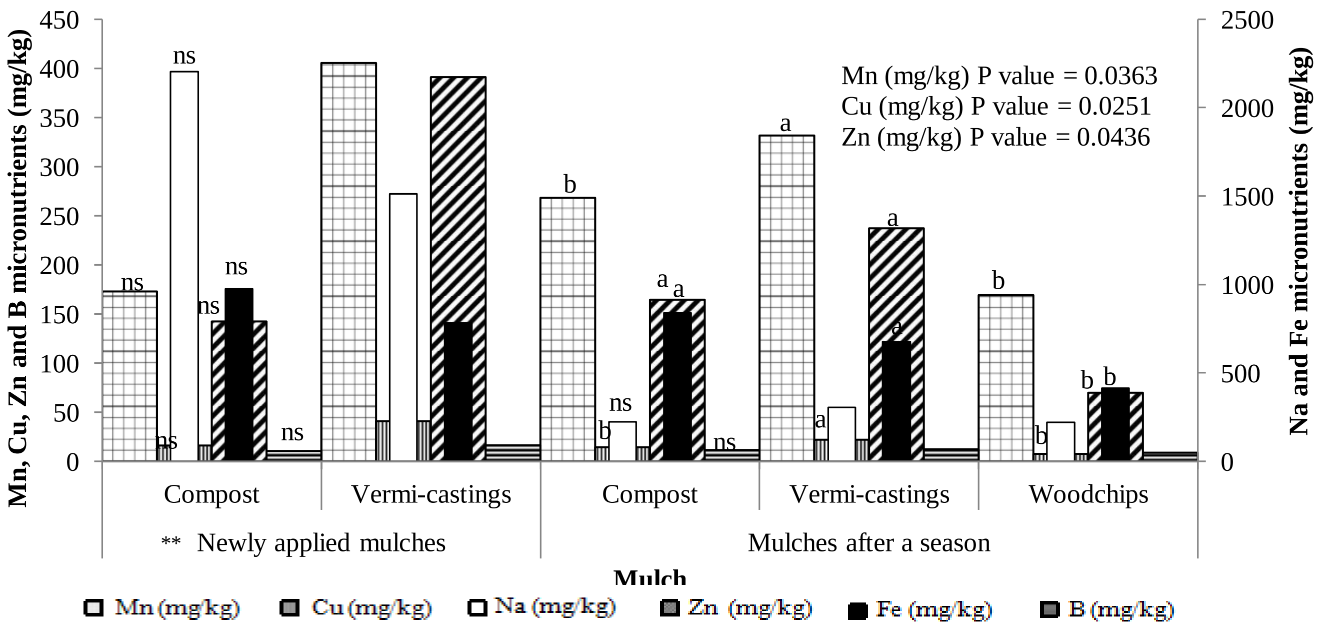

Fig. 4 Micronutrient mulch analysis of the newly applied mulches and the mulches after a season in 2012, at the lighter soil site

* Means with different small letters differed significantly at P<0.05. Means with "ns" were not significantly different.

** The woodchips mulch was not analyzed as a newly applied mulch due to the undecomposed nature of the material.

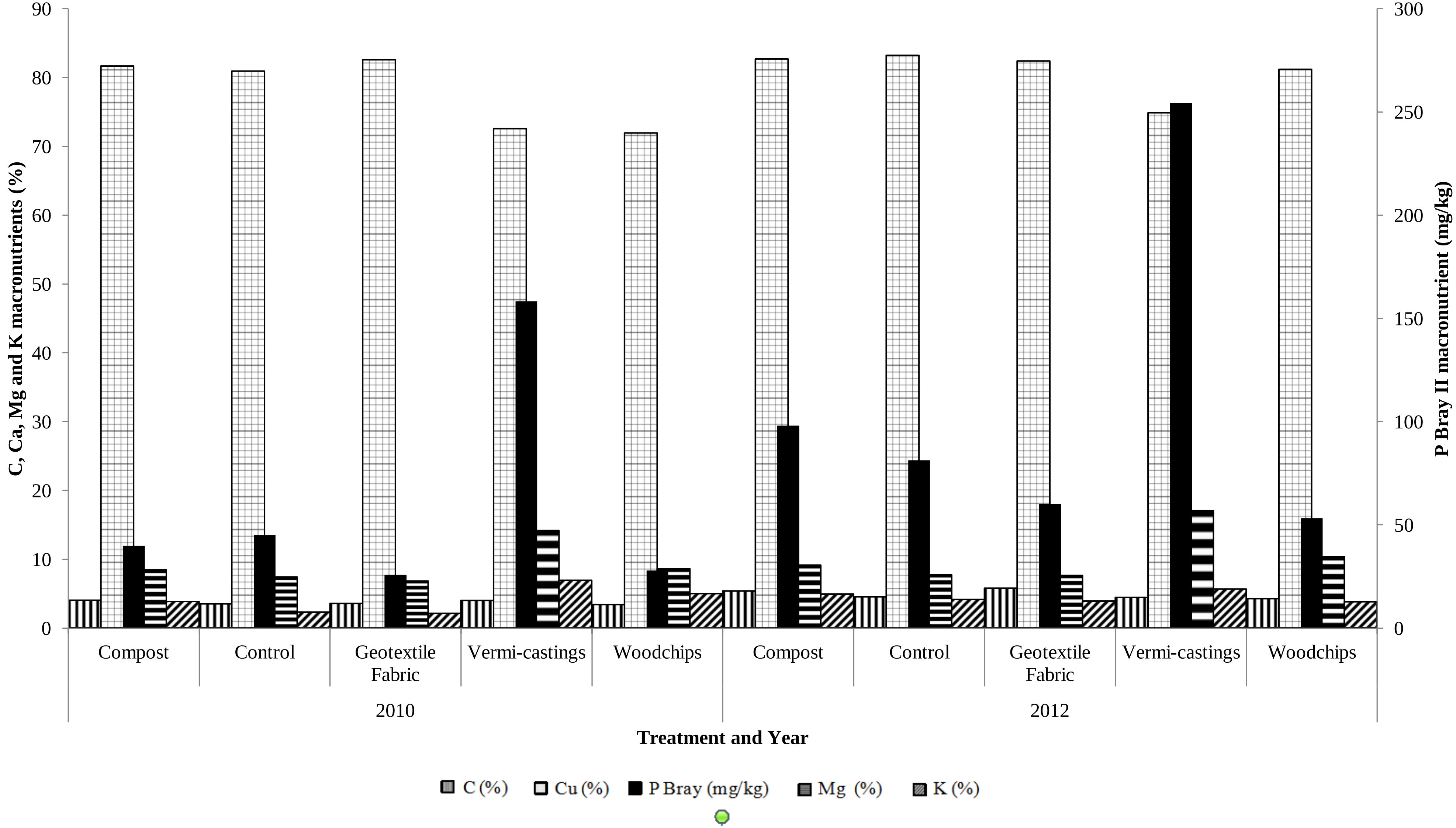

Fig. 5 Macronutrient analysis of the heavier soil site at a depth of 0 – 10 cm during 2010 to 2012

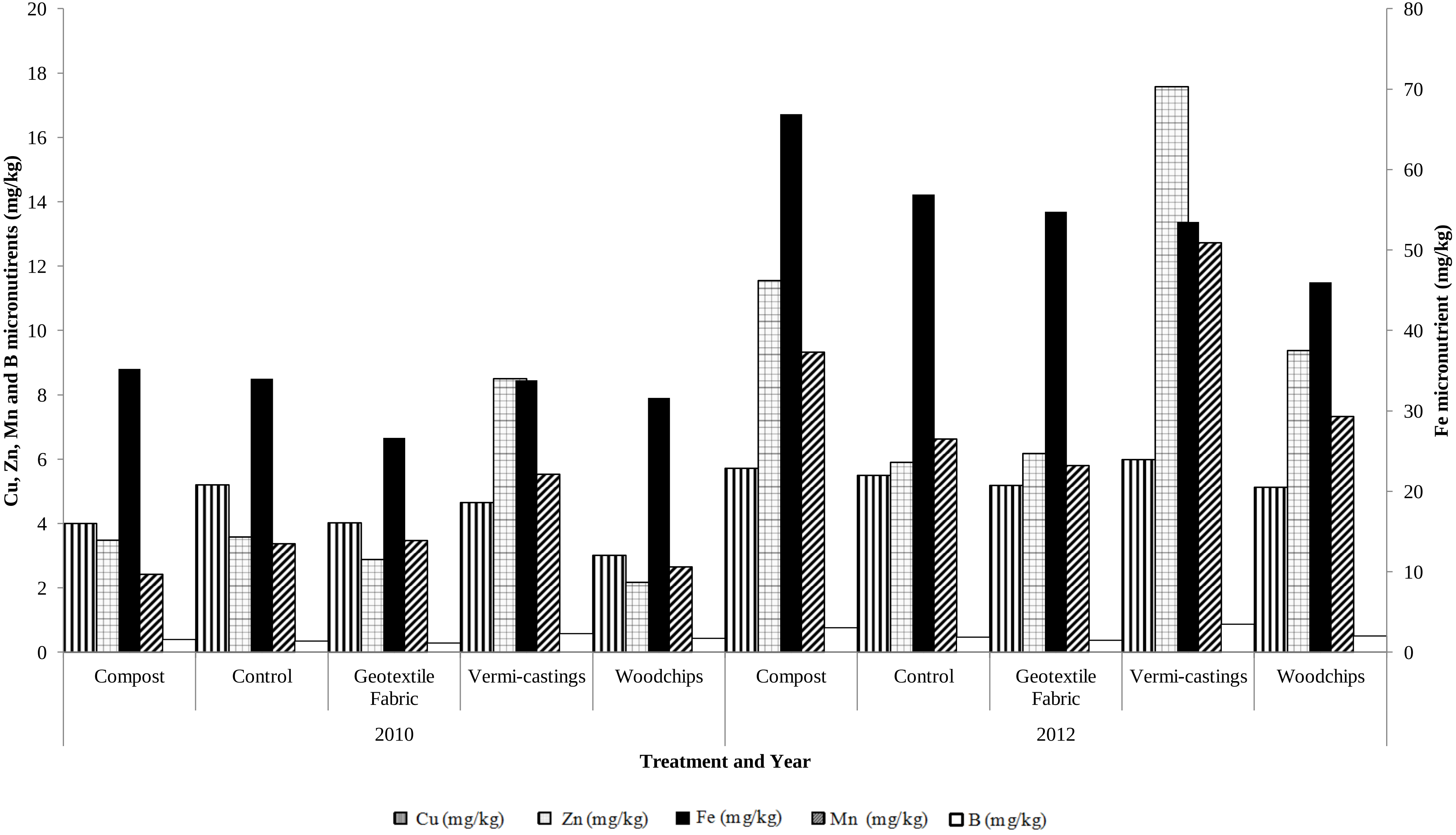

Fig. 6 Micronutrient analysis of the heavier soil site at a depth of 0 – 10 cm during 2010 to 2012

Table 1 Soil mineral analysis showing the pH, H ions and macro-elements at 0 – 10 cm depth in May 2012 in the heavier soil site

Treatment	pH (KCl)	H^+ (cmol/kg)	P BrayII (mg/kg)	C (%)	N (%)	K (cmol(+)/kg)	Ca (cmol(+)/kg)	Mg (cmol(+)/kg)
Compost	6.00^{A}	0.33^{ns}	98.00^{b}	5.38^{ns}	0.26^{A}	0.73^{ab}	12.22^{a}	1.36^{b}
Control	5.80^{AB}	0.42	81.25^{b}	4.53	0.21^{B}	0.45^{c}	9.00^{c}	0.81^{c}
Geotextile Fabric	5.68^{B}	0.47	60.00^{b}	5.79	0.23^{AB}	0.42^{c}	9.16^{c}	0.85^{c}
Vermi-castings	6.03^{A}	0.33	254.25^{a}	4.46	0.26^{A}	0.92^{a}	11.94^{ab}	2.75^{a}
Woodchips	5.80^{AB}	0.38	53.25^{b}	4.27	0.256^{A}	0.46^{bc}	9.78^{bc}	1.25^{bc}
p-value	0.0672	0.3056	0.0003	0.3619	0.0936	0.0077	0.0163	<.0001
LSD	0.27	0.16	73.20	1.86	0.04	0.28	2.20	0.50

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with “ns” were not significantly different.

Table 2 Soil mineral analysis showing the micro-elements and CEC at 0 – 10 cm depth in May 2012 in the heavier soil site

Treatment	Na (cmol(+)/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Fe (mg/kg)	CEC (pH 7) (cmol(+)/kg)
Compost	0.19^{ab}	5.72^{ns}	11.55^{b}	9.33^{b}	0.76^{ab}	66.90^{ns}	12.74^{a}
Control	0.15^{b}	5.50	5.90^{c}	6.63^{bc}	0.47^{bc}	56.92	8.92^{b}
Geotextile Fabric	0.17^{b}	5.18	6.18^{c}	5.80^{c}	0.37^{c}	54.76	10.69^{ab}
Vermi-castings	0.22^{a}	5.99	17.58^{a}	12.73^{a}	0.87^{a}	53.47	11.86^{a}
Woodchips	0.16^{b}	5.13	9.38^{bc}	7.33^{bc}	0.50^{bc}	45.98	11.23^{a}
p-value	0.0489	0.7308	0.0013	0.0054	0.0371	0.8125	0.0275
LSD	0.043	1.56	4.89	3.37	0.34	37.23	2.21

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with “ns” were not significantly different.

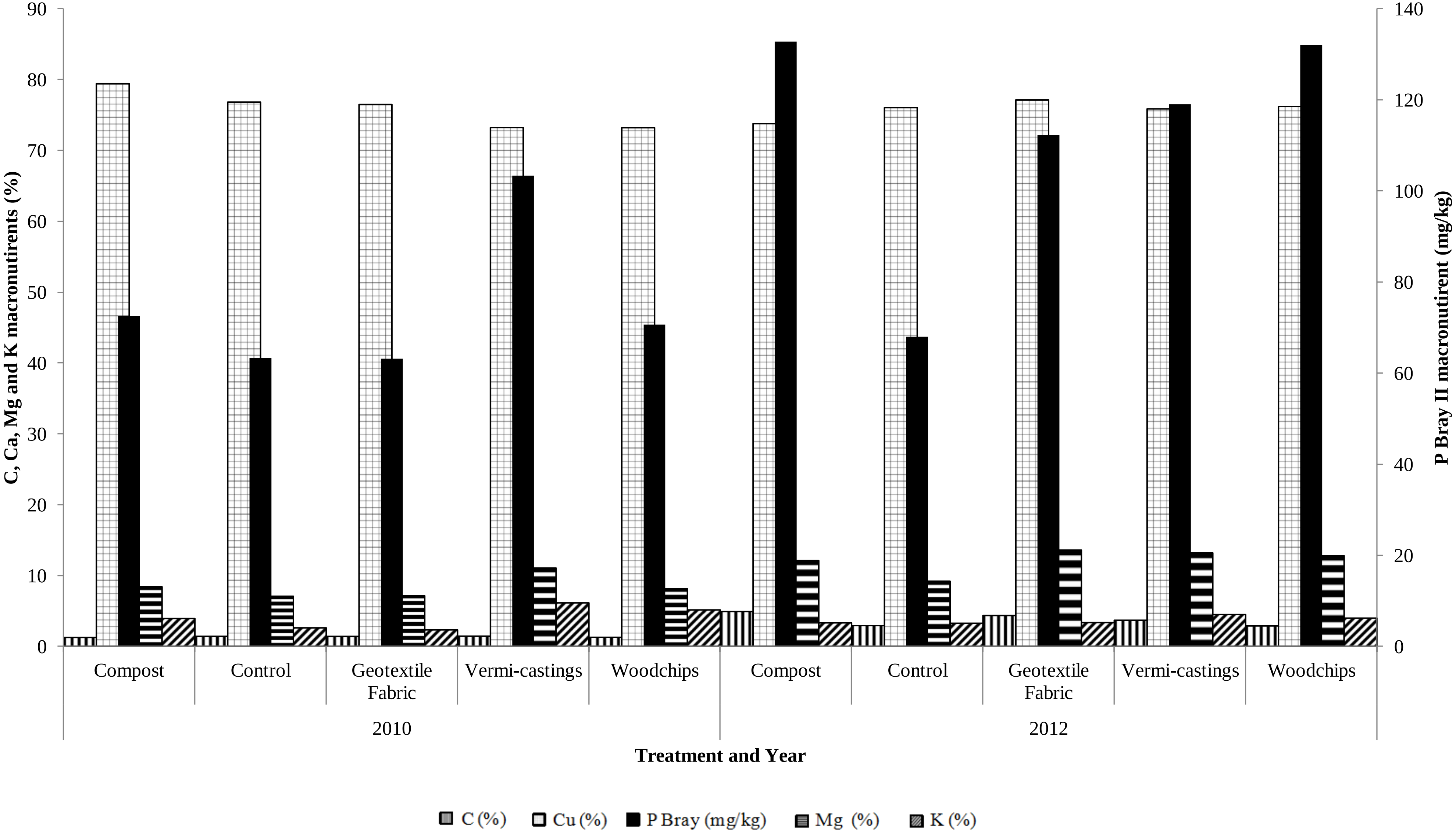

Fig. 7 Macronutrient analysis of the lighter soil site at a depth of 0 – 10 cm during 2010 to 2012

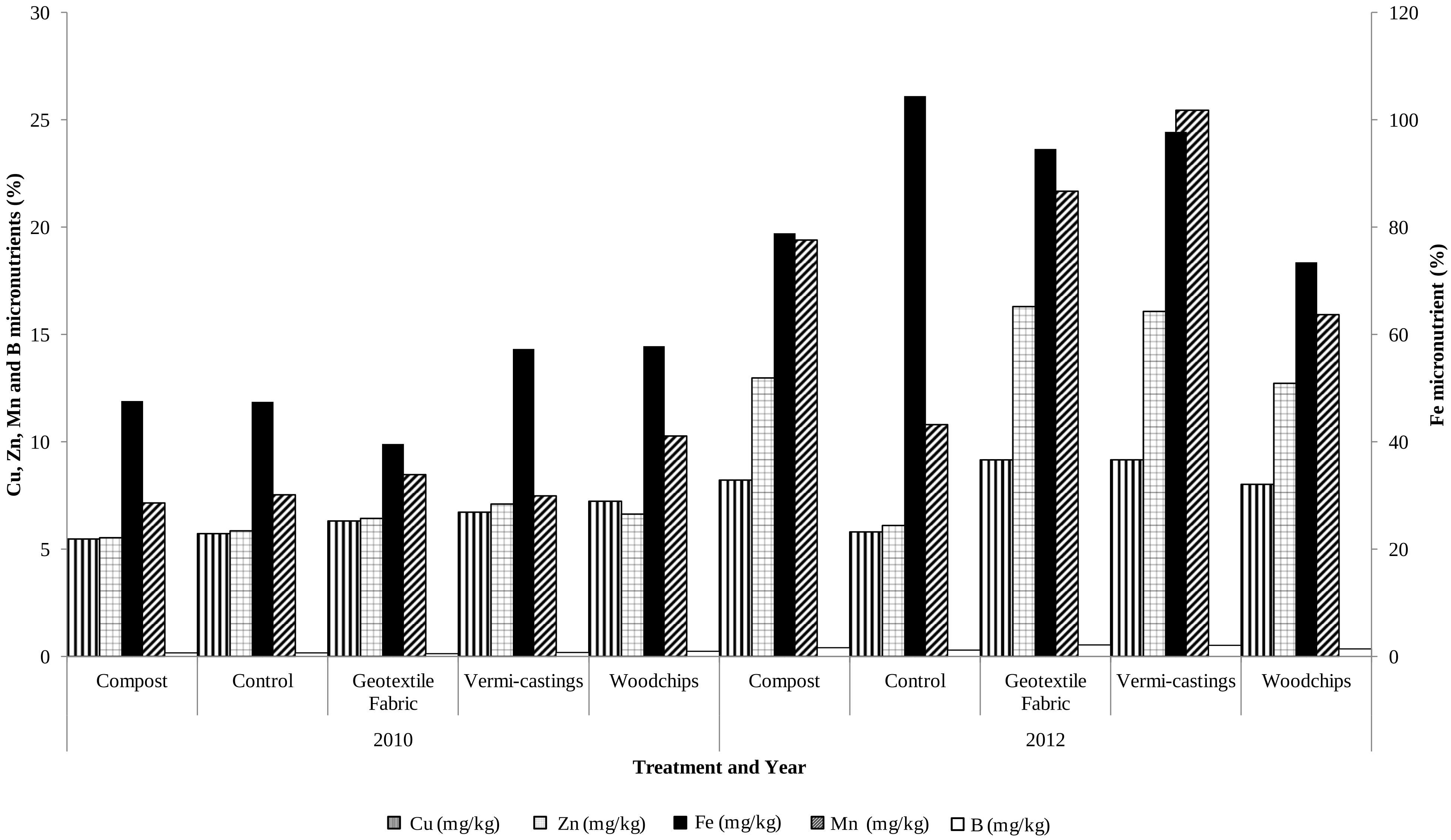

Fig. 8 Micronutrient analysis of the lighter soil site at a depth of 0 – 10 cm during 2010 to 2012

Table 3 Soil mineral analysis showing the pH, H ions and macro-elements at 0 – 10 cm depth in May 2012 in the lighter soil site

Treatment	pH (KCl)	H^+ (cmol/kg)	P BrayII (mg/kg)	C (%)	N (%)	K (cmol(+)/kg)	Ca (cmol(+)/kg)	Mg (cmol(+)/kg)
Compost	5.925[ns]	0.43[ns]	245.25[ns]	4.9025[a]	0.15[ns]	0.28[ns]	5.36[ns]	1.21[ns]
Control	5.65	0.51	117.75	2.8300[c]	0.13	0.22	4.36	0.64
Geotextile Fabric	6.15	0.40	235.25	3.7350[bc]	0.15	0.22	6.16	1.28
Vermi-castings	6.25	0.25	237.50	4.0325[ab]	0.16	0.35	6.98	1.33
Woodchips	5.80	0.38	219.25	3.3250[bc]	0.14	0.29	6.055	1.01
p-value	0.1505	0.2928	0.6592	0.0169	0.9118	0.8408	0.4349	0.5941
LSD	0.53	0.25	207.94	1.1146	0.05	0.28	2.98	1.024

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with “ns” were not significantly different.

Table 4 Soil mineral analysis showing the micro-elements and CEC at 0 – 10 cm depth in May 2012 in the lighter soil site

Treatment	Na (cmol(+)/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Fe (mg/kg)	CEC (pH 7) (cmol(+)/kg)
Compost	2.00[ns]	8.22[a]	12.98[ns]	19.40[ns]	0.41[ns]	78.87[ns]	5.67[ns]
Control	2.32	5.80[b]	6.10	10.80	0.30	104.47	6.25
Geotextile Fabric	1.72	9.16[a]	16.30	21.68	0.54	94.55	6.33
Vermi-castings	1.69	9.16[a]	16.08	25.45	0.52	97.79	5.90
Woodchips	1.86	8.02[a]	12.73	15.93	0.34	73.47	6.15
p-value	0.2186	0.0079	0.5687	0.2437	0.4753	0.6512	0.9614
LSD	0.61	1.76	14.53	13.73	0.33	50.96	2.19

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with “ns” were not significantly different.

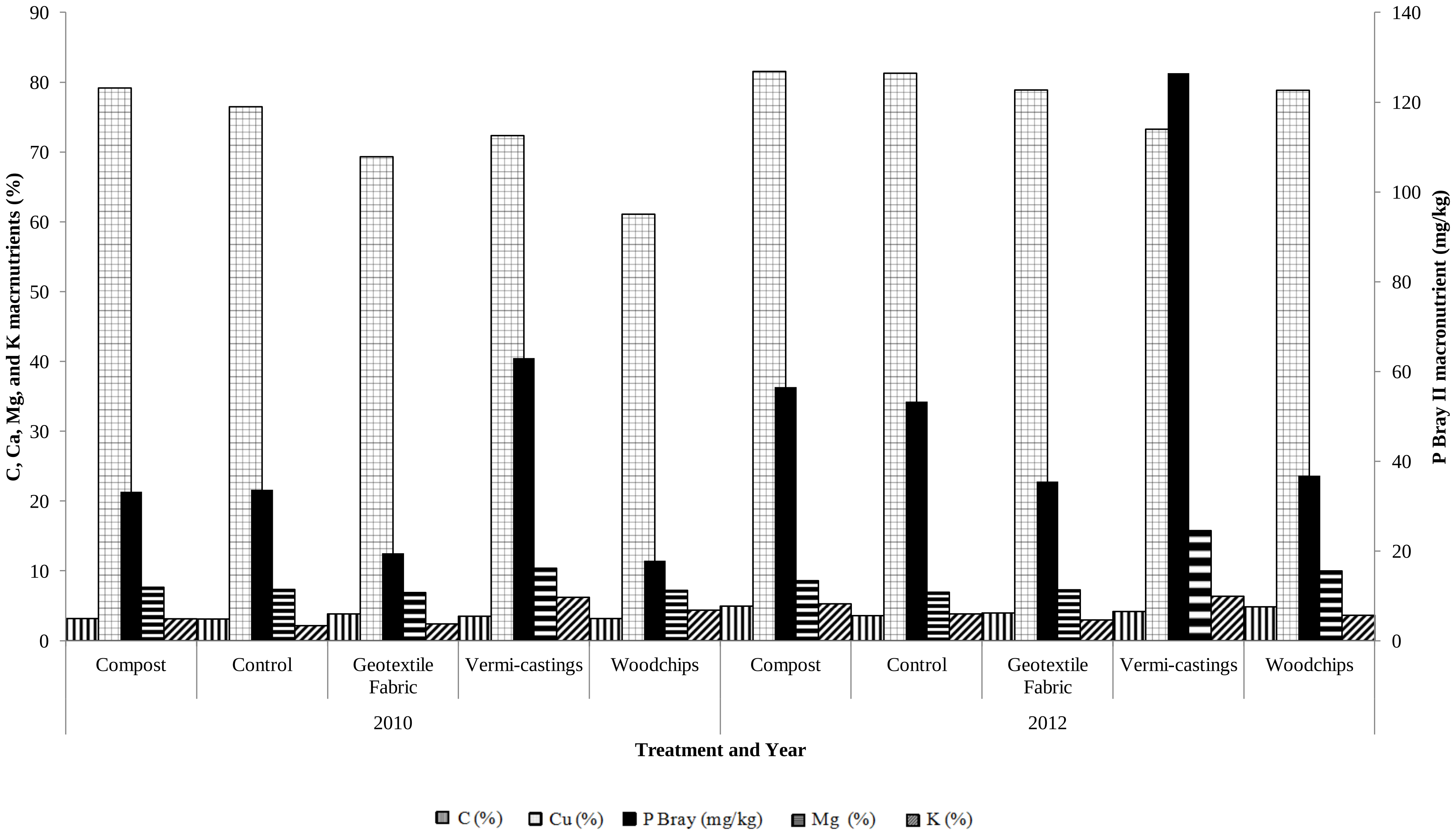

Fig. 9 Macronutrient analysis of the heavier soil site at a depth of 10 – 30 cm during 2010 to 2012

Table 5 Soil mineral analysis showing the pH, H ions and macro-elements at 10 – 30 cm depth in May 2012 in the heavier soil site

Treatment	pH (KCl)	H^+ (cmol/kg)	P BrayII (mg/kg)	C (%)	N (%)	K (cmol(+)/kg)	Ca (cmol(+)/kg)	Mg (cmol(+)/kg)
Compost	5.83^{A}	0.42^{ns}	56.50^{b}	4.95^{ns}	0.24^{ns}	0.62^{ab}	9.52^{ns}	1.01^{b}
Control	5.65^{AB}	0.48	53.25^{b}	3.58	0.20	0.34^{c}	7.45	0.62^{b}
Geotextile Fabric	5.38^{B}	0.65	35.50^{b}	3.97	0.22	0.24^{c}	6.77	0.62^{b}
Vermi-castings	5.85^{A}	0.35	126.50^{a}	4.18	0.25	0.83^{a}	9.3	2.05^{a}
Woodchips	5.48^{AB}	0.58	36.75^{b}	4.85	0.25	0.36^{bc}	7.90	1.00^{b}
p-value	0.0964	0.1047	0.0028	0.2406	0.2170	0.0029	0.1489	0.0003
LSD	0.41	0.24	41.92	1.43	0.05	0.27	2.57	0.50

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 6 Soil mineral analysis showing the micro-elements and CEC at 10 – 30 cm depth in May 2012 in the heavier soil site

Treatment	Na (cmol(+)/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Fe (mg/kg)	CEC (pH 7) (cmol(+)/kg)
Compost	0.20^{ns}	4.57^{ns}	6.45^{b}	7.30^{b}	0.69^{AB}	107.46^{ns}	11.54^{ns}
Control	0.15	4.11	3.03^{c}	4.30^{c}	0.46^{BC}	55.10	10.31
Geotextile Fabric	0.16	3.66	3.20^{c}	4.30^{c}	0.36^{C}	50.36	11.62
Vermi-castings	0.21	4.80	10.53^{a}	10.08^{a}	0.76^{A}	54.69	11.91
Woodchips	0.16	4.23	5.08^{bc}	5.60^{bc}	0.54^{ABC}	54.75	11.54
p-value	0.1063	0.7346	0.0004	0.0012	0.0695	0.2169	0.4160
LSD	0.048	1.91	2.72	2.47	0.30	57.17	1.85

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

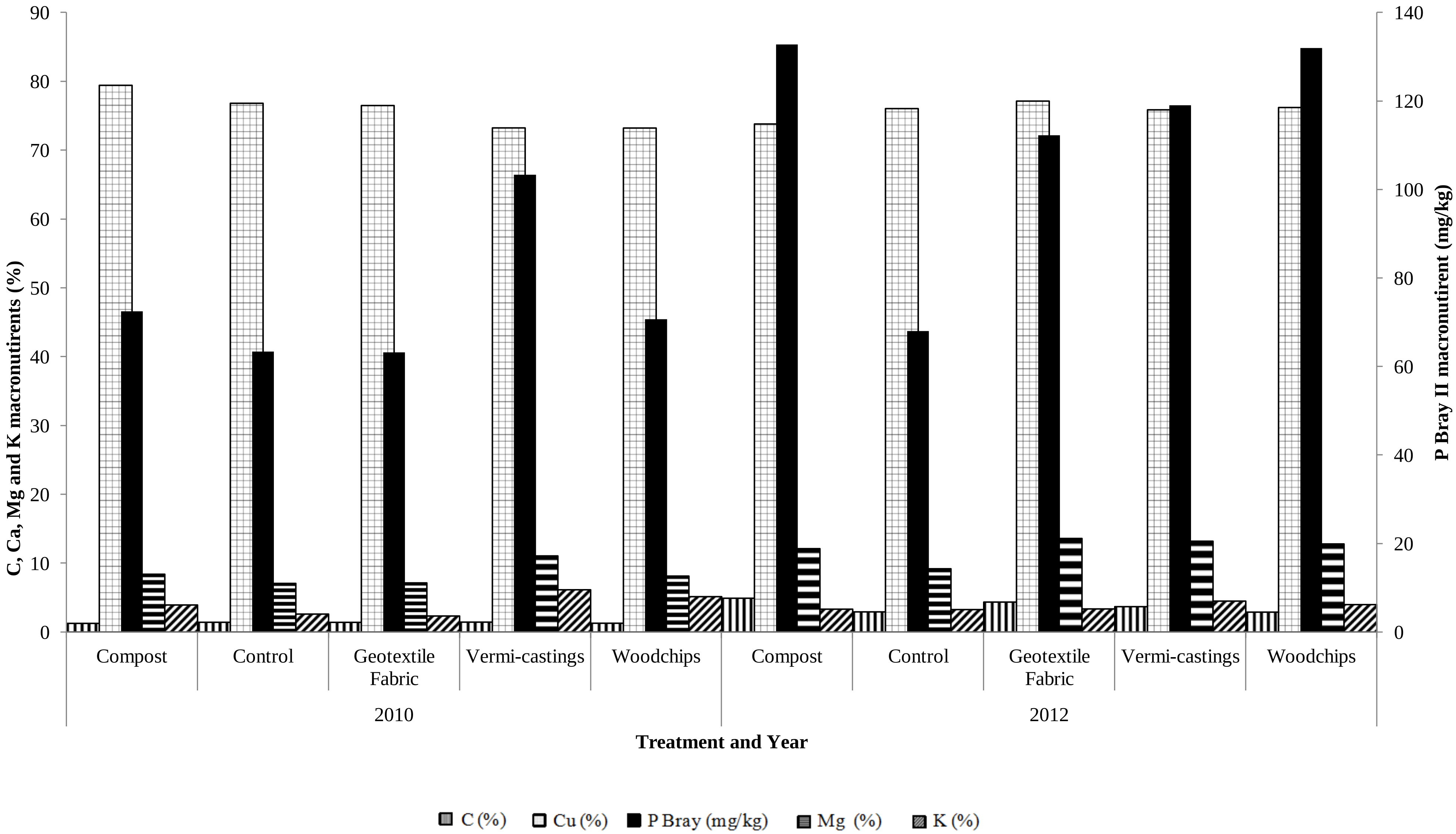

Fig. 10 Macronutrient analysis of the lighter soil site at a depth of 10 – 30 cm during 2010 to 2012

Table 7 Soil mineral analysis showing the pH, H ions and macro-elements at 10 – 30 cm depth in May 2012 in the lighter soil site

Treatment	pH (KCl)	H^+ (cmol/kg)	P BrayII (mg/kg)	C (%)	N (%)	K (cmol(+)/kg)	Ca (cmol(+)/kg)	Mg (cmol(+)/kg)
Compost	5.80^{ns}	0.55^{ns}	132.75^{ns}	4.90^{a}	0.13^{ns}	0.21^{ns}	4.37^{ns}	0.78^{ns}
Control	5.70	0.46	68.00	2.92^{b}	0.12	0.17	4.20	0.51
Geotextile Fabric	6.00	0.42	112.25	4.34^{ab}	0.13	0.22	4.80	0.92
Vermi-castings	6.03	0.33	119.00	3.68^{ab}	0.13	0.29	4.81	0.84
Woodchips	5.85	0.41	132.00	2.88^{b}	0.13	0.27	5.02	0.84
p-value	0.7045	0.4525	0.6269	0.0463	0.6485	0.8717	0.8320	0.7779
LSD	0.57	0.25	100.03	1.49	0.02	0.26	1.75	0.73

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 8 Soil mineral analysis showing the micro-elements at 10 – 30 cm depth in May 2012 in the lighter soil site

Treatment	Na (cmol(+)/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Fe (mg/kg)	CEC (cmol(+)/kg)
Compost	0.14^{ns}	5.40^{ns}	6.13^{ns}	9.95^{ns}	0.37^{ns}	90.51^{ns}	4.49^{ns}
Control	0.13	4.89	3.65	6.03	0.31	96.05	5.85
Geotextile Fabric	0.13	7.55	7.18	12.13	0.44	90.46	5.09
Vermi-castings	0.15	6.09	6.08	11.65	0.43	82.44	5.09
Woodchips	0.14	6.09	6.40	9.45	0.36	97.09	6.06
p-value	0.2671	0.2398	0.6817	0.4189	0.7260	0.9814	0.2377
LSD	0.03	2.45	5.35	7.22	0.24	57.65	1.55

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 9 Soil mineral analysis showing the pH, H ions and macro-elements at 30 – 50 cm depth in May 2012 in the heavier soil site

Treatment	pH (KCl)	H^+ (cmol/kg)	P BrayII (mg/kg)	C (%)	N (%)	K (cmol(+)/kg)	Ca (cmol(+)/kg)	Mg (cmol(+)/kg)
Compost	5.60^{AB}	0.49^{ns}	40.50^{b}	4.34^{ns}	0.23^{AB}	0.50^{a}	8.14^{ns}	0.88^{b}
Control	5.50^{AB}	0.55	36.50^{b}	3.83	0.18^{B}	0.30^{b}	6.58	0.58^{b}
Geotextile Fabric	5.28^{B}	0.68	35.00^{b}	4.15	0.21^{AB}	0.22^{b}	6.17	0.64^{b}
Vermi-castings	5.73^{A}	0.42	103.50^{a}	4.50	0.22^{AB}	0.69^{a}	7.84	1.54^{a}
Woodchips	5.33^{B}	0.82	31.75^{b}	4.11	0.25^{A}	0.29^{b}	7.02	0.83^{b}
p-value	0.0573	0.2452	0.0154	0.7744	0.0917	0.0016	0.1114	0.0049
LSD	0.33	0.39	42.80	1.18	0.05	0.20	1.67	0.46

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 10 Soil mineral analysis showing the micro-elements at 30 – 50 cm depth in May 2012 in the heavier soil site

Treatment	Na (cmol(+)/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Fe (mg/kg)	CEC (pH 7) (cmol(+)/kg)
Compost	0.21^{ns}	3.65^{ns}	4.08^{b}	5.43^{b}	0.52^{AB}	100.88^{ns}	10.79^{ns}
Control	0.16	3.27	1.95^{b}	3.00^{c}	0.40^{B}	72.31	9.32
Geotextile Fabric	0.16	3.16	2.63^{b}	4.05^{bc}	0.45^{B}	51.78	10.11
Vermi-castings	0.18	4.44	8.55^{a}	9.13^{a}	0.65^{A}	58.01	11.05
Woodchips	0.17	3.49	3.28^{b}	4.08^{bc}	0.50^{AB}	53.28	10.67
p-value	0.2065	0.4611	0.0045	0.0009	0.0770	0.1400	0.4631
LSD	0.05	1.58	3.11	2.34	0.17	43.25	2.17

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 11 Soil mineral analysis showing the pH, H ions and macro-elements at 30 – 50 cm depth in May 2012 in the lighter soil site

Treatment	pH (KCl)	H^+ (cmol/kg)	P BrayII (mg/kg)	C (%)	N (%)	K (cmol(+)/kg)	Ca (cmol(+)/kg)	Mg (cmol(+)/kg)
Compost	5.73^{ns}	0.60^{ns}	110.00^{ns}	4.46^{ns}	0.12^{ns}	0.17^{ns}	4.02^{ns}	0.70^{ns}
Control	5.75	0.41	46.75	2.69	0.12	0.15	4.13	0.50
Geotextile Fabric	5.85	0.46	80.50	3.96	0.12	0.19	4.35	0.73
Vermi-castings	5.93	0.38	84.25	3.57	0.13	0.28	4.26	0.72
Woodchips	5.63	0.50	78.75	9.09	0.13	0.16	4.58	0.70
p-value	0.7265	0.4040	0.6276	0.5058	0.9062	0.7960	0.9368	0.8946
LSD	0.50	0.25	84.96	8.25	0.03	0.24	1.50	0.59

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 12 Soil mineral analysis showing the micro-elements at 30 – 50 cm depth in May 2012 in the lighter soil site

Treatment	Na (cmol(+)/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Fe (mg/kg)	CEC (pH 7) (cmol(+)/kg)
Compost	0.14^{ns}	5.13^{ns}	5.80^{ns}	10.98^{ns}	0.38^{ns}	110.93^{ns}	5.48^{ns}
Control	0.14	4.34	2.33	4.70	0.33	91.87	6.17
Geotextile Fabric	0.13	5.52	4.03	7.93	0.36	110.93	4.88
Vermi-castings	0.16	5.67	4.55	10.36	0.41	157.57	4.94
Woodchips	0.13	4.45	4.00	7.13	0.28	102.24	5.97
p-value	0.4065	0.7697	0.7464	0.6111	0.5205	0.7695	0.2735
LSD	0.04	2.79	5.53	9.42	0.17	118.91	1.49

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Paper 3

The effect of organic and inorganic mulches on mycorrhizae colonization and nematode populations in the root environment of 'Cripps' Pink' apple trees.

Introduction

The biological status of the soil is largely influenced by cultivation practices, many of which decrease micro- and macro-organism populations. However, certain mulches can be beneficial to the biological status and fertility of the soil (Lakatos et al. 2001; Nagy et al. 2008).

There are many different functional organism groups in the soil including: fungi, mycorrhizae, bacteria, protozoa, nematodes, micro-arthropods and higher level insects, all of which make up the soil food web (Storey and Hugo 2010). The soil food web works on a production-decomposition basis where organisms are grouped as root-feeders, shredders, predators and generalists (Storey and Hugo 2010). Organisms are divided into taxa depending on their size. Mycorrhizae and nematodes are examples of microflora and microfauna respectively (Brussaard 1997). Quantifying soil biology is highly complex due to the diversity of the soil food web (Lacroix and Abbadie 1998). For the purpose of this paper, only mycorrhizae and nematode populations were quantified.

The colonization of root by mycorrhizae is generally a symbiotic relationship where the mycorrhizae increase the root surface area for nutritional uptake, particularly that of P. In return, the roots are a source of carbohydrates for the fungi (Gerdemann 1974). The relationship is beneficial for both roots and mycorrhizae, provided it remains balanced (Gerdemann 1974). The suppression of mycorrhizae populations is accompanied by conditions of dry, water-logged, or saline soils, as well as conditions of extreme soil fertilities (Taiz and Zeiger 2010). The host plant can also suppress populations in case of sufficient soil fertility, preventing the relationship from becoming pathogenic (Taiz and Zeiger 2010). Due to the enhancement of the root environment that mulches provide, the root surface area is often increased, allowing more colonization. However, the type of mulch used can have a significant influence on the extent of mycorrhizal colonisation of the roots and some mulches have been found to have an adverse effect on colonization (Lakatos et al. 2001; Derkowska et al. 2008). This is often due to high concentrations of certain nutrients i.e. phosphorus that some mulching materials add to the root zone (Lakatos et al. 2001).

Of all the organisms of the metazoa, nematodes are the most abundant and are divided at family level according to their morphology and nature of feeding (Brussaard 1997; Storey and Hugo 2010). Bacteriovores, fungivores, herbivores, omnivores and carnivores make up the diverse communities of nematodes found in soils (Brussaard 1997; Storey and Hugo 2010). Not all nematodes are therefore parasitic to plants; some are also beneficial to agriculture as they feed on unfavourable fungi and bacteria in the soil (Storey and Hugo 2010). Herbivorous nematodes are classified as plant pathogenic nematodes, where as all of the other families of nematodes that do not impact the plant directly, are classified as free-living nematodes. Due to the simple and cost effective nature of sampling, extracting and identifying nematodes, as opposed to other soil fauna, they are an effective way to indicate soil health (Neher 2001). With the potential increase in organic matter in the soil, accompanied with the use of organic mulches, more food is made available to free-living nematodes, particularly at surface level, and thus their populations are inclined to increase. In addition to this, however, root systems are also known to increase under certain mulches, which also enable herbivorous nematode populations to increase. Nematodes are reported to react quickly to new resources (Storey and Hugo 2010), thus their population increases due to a soil amendment such as mulches is highly likely.

Due to the direct effect mulching has on other properties of the soil, such as temperature and soil water, and the resulting effect on root growth, it is hypothesised that the mycorrhizal and nematode populations will be influenced indirectly by the use of mulches. The aim of this paper was to quantify these changes in the root environment of two soil types as a result of mulching over a period of four seasons.

Materials and Methods

Trial Layout

The trail was carried out at Lourensford Estate, Somerset West, South Africa (-34° 2' 31.29", +18° 55' 16.20") and commenced in October 2008 (Kotze et al. 2012). The trial consisted of two 'Cripps' Pink' apple orchards planted in 1998 on M793 rootstocks on two different soil types. One site was on a heavier soil (Clovelly) and the other, an adjacent orchard, on a lighter soil (Tukulu).

The trial layout was a randomized complete block design with 5 treatments, 6 blocks, repeated on the 2 sites. Two buffer trees were added between plots to differentiate clearly between each plot. Each plot comprised four trees.

Of the five treatments, three were mulches consisting of organic materials, one of an inorganic material and the remaining one was the control, with no mulch. The organic mulches were as follows: wood chips containing no initial significant nutrient levels and originating from various tree species (excluding pine as it is known to leach allelochemicals); compost, where the nutrient levels were determined and vermi-castings (also with determined nutrient composition) with wood chips placed on top to prevent loss of the castings due to rain or wind. The inorganic mulch was a black polytex PT110 woven geotextile fabric that allowed water and nutrients to penetrate the soil, but contained no nutrient levels itself. The control treatment was not mulched and was under clean cultivation, where weeds were controlled according to farm management.

Normal commercial practises were followed regarding orchard management, apart from the irrigation. In January 2011 every second 42 ℓ h^{-1} micro-jet was replaced with a 20 ℓ h^{-1} micro-jet, reducing the deliverance of water due to suspected over irrigation, which became evident from historical data (Kotze et al. 2012). In October 2011 it was decided to further reduce irrigation, based on data acquired from FruitLook satellites, which was only available from 2011 and illustrated a lack of evapotranspiration deficit in both sites (fruitlook.co.za) (data in Paper 1), and thus the deliverance was further reduced by replacing every 42 ℓ h^{-1} micro-jet in the trial with 20 ℓ h^{-1} micro-jet. Evapotranspiration deficit is a measure of plant water stress. Although under normal crop production condition, plant water stress is not usually favourable, due to the nature of the trial and the use of mulching which essentially is a water conservation tool, a certain amount of water stress was require in order to receive results with regard to the mulches. The change in irrigation volumes, however, did not result in water reductions to the extent that would inflict stress on the control plots. The only spikes in evapotranspiration deficit were noted in times of heat waves where ambient temperatures reached upper thirties. The irrigation scheduling was maintained by the farm manager at two hours, three times per week, however irregularities in the irrigation scheduling were found during visits to the sites on various occasions.

Application of Mulches

Organic mulches were reapplied every year from trial commencement in October (2009 – 2011) to maintain a thickness of approximately 5cm on the soil surface. The inorganic mulch treatment, black polytex PT110 woven geotextile fabric, remained from the commencement of the trial.

A total of 90 ℓ of compost and woodchips respectively were evenly dispersed over their respective treatments per block during each reapplication. A total of 60 ℓ of vermi-castings, topped with 30 ℓ of woodchips, were evenly dispersed per block for the vermi-castings treatment.

Mychorrizal Study

Fine root samples were taken in April 2010 (Kotze et al. 2012), 2011 and 2012 for mycorrhizal studies and were analyzed according to the staining protocol of Giovannetti and Mosse (1980). Four replicate samples per treatment, per site, were taken at 15 cm depth. Samples were cleared of soil particles with distilled water before being preserved in 50% EtOH before staining.

The protocol required sample of 1 g – 2 g for effective staining. Prior to staining, the root samples were weighed to ensure that they did not exceed 2 g. Samples were cleared of remaining soil with 10% v/w KOH (10g KOH + 100ml distilled water) in a 15 minute liquid cycle in the autoclave at 121°C. Once removed from the autoclave, roots were then captured on a sieve and rinsed with distilled water. Post clearing bleaching is sometimes required in the event that roots are not completely cleared of soil. This is done by rinsing the roots with 0.5% NH_4OH (0.5ml of stock containing: 3ml NH_4OH; 10ml 30% H_2O_2; 587ml distilled water, mixed with 100ml distilled water) followed by distilled water, until the roots discolour. Discoloured roots were stained with 0.05% v/w aniline blue (0.05g aniline blue + 100ml lactoglyceral solution) in a 15 minute cycle in the autoclave at 121°C. Prior to observation samples require a degree of distaining to remove excess aniline blue. This was done by rinsing them with 50% glycerol (50ml glycerol + 50ml distilled water) over a mesh fabric.

Analysis was done according to the slide method of assessment of Giovannetti and Mosse (1980). Stained root samples were dispersed on a petri dish and 1 cm long pieces were cut with a scalpel and mounted in groups of 10 per block in 50% ethanol on microscope slides. Slides were analysed with a compound light microscope at 200 X magnification. Presence or absence of mycorrhizal infection was recorded and expressed as percentage colonization per sample.

Nematode Study

Nematode presence was evaluated by the ARC Infruitec- Nietvoorbij in April 2009 (Kotze et al. 2012), 2010 (Kotze et al. 2012), 2011 and 2012. Two sub samples per plot were pooled to create a composite sample at depths of 0 – 15 cm and 15 – 30 cm respectively. Jenkins (1964) centrifugal-flotation extraction method was used to analyse a 250 cm^3 soil sample, to separate the nematodes from the soil, after which the sample size was reduced to 20 ml following a settlement period of 1 hour. The numbers of nematodes in 2 x 1 ml extractions were identified with a compound light microscope. Plant parasitic nematodes were identified into gene level and the non parasitic nematodes were grouped together as free living nematodes.

Statistical Analysis

All data that was of a statistical nature (mycorrhizae study and the nematode study) was analyzed using the Statistical Analysing System (SAS) programme 9.1 (SAS Institute Inc, 2004, Cary, NC). Analyses of variances were analyzed using a General Linear Model (GLM) procedure and standard errors and least square means were calculated for each treatment. Data was considered significant at a 5% significance level and 10% significance level where specified.

Results

Mycorrhizal Study

Historical mycorrhizal data from 2010, adapted from Kotze et al. (2012), was used along with data from 2011 and 2012 for the mycorrizal interpretation (Table 1 and 2).

Significant differences between treatments, with regards to percentage mycorrhizal colonization, occurred in the heavier soil site in 2011 ($P = 0.0857$) and 2012 ($P = 0.0466$) (Table 1). Trends were evident from 2010 to 2012, including an overall reduction in percentage mycorrhizea colonization that occurred in 2011. Colonies increased again in 2012. The geotextile fabric and compost treatments had significantly higher percentage colonies in 2011 than the vermi-castings treatment which had the lowest percentage. The control and woodchips treatments did not differ significantly from any of the treatments. In 2012 the vermi-castings treatment resulted in significantly lower percentage colonies again and the geotextile fabric and compost treatments resulted in significantly higher percentage colonies. The woodchips treatment also for a second time did not differ significantly from any of the treatments.

Significant differences between treatments, with regards to mycorrhizal colonization, occurred in the lighter soil site in 2010 ($P = 0.0016$) and 2011 ($P = 0.0121$) (Table 2). Similarly to the heavier soil site, an overall reduction in percentage mycorrhizea colonization occurred in 2011, however, a different trend was noted from 2010 to 2011. Colonies increased again in 2012. The control treatment had significantly lower percentage colonies in 2010 compared to the other treatments, which did not differ significantly from each other. In 2011 the control treatment had significantly lower percentage colonies again, but only differed significantly from the organic mulch treatments. The compost treatment resulted in significantly higher percentage colonies.

Nematode Study

Historical nematode data from 2009 and 2010, adapted from Kotze et al. (2012), was used along with data from 2011 and 2012 for the nematode analysis (Fig. 1 – 4). The purpose of these figures is to display a trend over time.

0 – 15 cm

In the heavier soil site there was no obvious trend from 2009 to 2012 in the 0 – 15 cm soil layer, other than an overall decrease in plant parasitic nematodes from 2009 to 2010 and then increase from 2010 to 2012, as well as an overall increase in free-living nematodes from 2009 to 2010 and then decrease from 2010 to 2012 over all of the mulched treatments (Fig. 1). The decrease in plant parasitic nematodes from 2009 to 2010, returned to similar levels in 2011 again. The free-living nematodes in 2011, however, were less than what they were before their increase in 2010. The increase in plant parasitic nematodes and decrease in free-living nematodes particularly occurred from 2010 to 2011 and then remained fairly constant from 2011 to 2012. The same trend occurred in the control treatment, however, to a lesser degree.

The woodchips and compost treatments resulted in the greatest shift towards larger percentage plant parasitic nematodes in 2012. The woodchips mulch incurred the greatest drop in percentage free-living nematodes and the greatest gain in plant parasitic nematodes from 2010 to 2012. In contrast to its organic mulch counterparts, the vermi-castings treatment was the most consistent treatment in keeping its free-living percentage nematodes well in the majority for all three years. No significant differences between treatments occurred in the free-living and plant parasitic nematodes in 2011 and 2012 (Table 3).

A similar trend occurred from 2009 to 2012 in the 0 – 15 cm soil layer of the lighter soil site as in the heavier soil site, however, instead of remaining constant from 2011 to 2012, the plant parasitic nematodes decreased and the free-living nematodes increased to a greater degree (Fig. 2). The woodchips treatment realized the most notable change over the four seasons as its percentage populations shifted more dramatically, however, following the same trend as the other treatments. The woodchip treatment untimely resulted in the smallest percentage plant parasitic nematodes in 2012. In 2011 the compost treatment resulted in a significantly higher percentage of free-living nematodes compared to the other treatments (P 0.033), with the exception of the vermi-castings treatments which did not differ significantly from any of the treatments (Table 4). In 2012, however, the compost treatment also had a significantly higher *Trichoderma* population which differed significantly from all of the treatments.

15 – 30 cm

Percentage nematodes generally remained constant from 2009 to 2012 in the 15 – 30 cm soil layer of the heavier soil site, with the exception of the compost treatment which realised a considerable increase in plant parasitic nematodes in 2012 (Fig. 3). An overall slight decrease in percentage plant parasitic nematodes occurred in 2011, which increased again in 2012. The compost treatment incurred the greatest shift in populations, having one of the lowest percentage plant parasitic nematodes in 2009 and 2010 and then the highest in 2012, surpassing the free-living nematodes. As seen in the 0 – 15 cm soil layer in this site, the vermi-castings treatment was consistent in keeping the percentage plant parasitic nematodes down. In 2012 significant differences occurred between treatments in the number of free-living nematodes ($P = 0.0837$) and the number of *Trichoderma spp.* nematodes (Table 5). The woodchips treatment realized a significantly higher population of free-living nematodes and the control treatment realized a significantly higher population of *Trichoderma spp.* nematodes. The other treatments did not differ between each other.

A similar trend to the 0 – 15 cm soil layer of the lighter soil site occurred in the 15 – 30 cm soil layer from 2009 to 2012, however, the changes occurred to a lesser degree and the geotextile fabric treatment incurred a considerable increase in plant parasitic nematodes from 2009 to 2010 (Fig. 4). The woodchips treatment also realized the most notable change over the three seasons at this depth and ultimately resulted in the lowest population of plant parasitic nematodes in 2012. No significant differences between treatments occurred in the free-living and plant parasitic nematodes in 2011 and 2012 (Table 6).

Discussion

Mycorrhizal Study

Due to the symbiotic nature of the mycorrhizae – root relationship, the invasion of the fungi is not pathological, provided the balanced relationship remains (Gerdemann 1974). In fertile soils, particularly with abundant P, soil conditions suppress mycorrhizae colonies due to plentiful P (Derkowska et al. 2008; Taiz & Zeiger 2010). Derkowska et al. (2008) mentioned that the extent of colonisation is dependent on the age of the roots and environmental conditions and may change from year to year. Colonisation may also be delayed as a result of environmental conditions. Mycorrhizea colonies are therefore likely to fluctuate from year to year for various reasons, including the surrounding nutrient status of the soil. This may explain the decrease in percentage colonization in both sites, particularly in the mulched treatments, noted from 2010 to 2011. As seen in the mineral analysis (data in Paper 2), overall increases in nutrients, particularly that of P, took place from 2010 to 2012, thus reducing the need for mycorrhizea.

In the heavier soil site, the vermi-castings treatment resulted in a significantly lower colonization percentage (40 – 60%) in 2011 and 2012, whereas the compost and geotextile fabric treatments resulted in a significantly higher colonization percentage (77.5% and 80% respectively) in 2011 and the compost and control treatments (92% and 85% respectively) in 2012. With reference to the mineral analysis performed in 2012 (data in Paper 2), the vermi-castings treatment had a significantly higher P contents compared to the other treatments.

Although we only have the soil mineral P contents for 2012, the decrease in percentage colonization in the vermi-castings treatment in 2011 and 2012 was possibly also due to high P levels. This corresponds with remarks by Derkowska et al. (2008) and Taiz and Zeiger (2010). Derkowska et al. (2008) found the lowest percentage colonization on strawberry roots in mulched treatments and highest in the control treatment.

Resembling the heavier soil site, the compost treatment also resulted in a significantly higher colonization percentage in 2010 and 2011 (95.0% and 80.0% respectfully) in the lighter soil site. In contrast to the heavier soil site the control treatment resulted in significantly lower colonization in the respective years (75.0% and 42.5%). The inconsistent results between the two sites confirms work from Derkowska et al. (2008) that mycorrhizea colonization is dependent on environmental conditions, of which, the different textured soils could have played a role in altering these conditions. They also emphasised that mycorrhizal colonisation is increased with greater root surface area and the growth of fine feeder roots. Due to the coarser nature of the soil in the sandy silt loam site, more roots will probably occur under the organic mulches as appose to the inorganic mulch or no mulch, where the organic matter content of these treatments is likely to be higher. Thus the increased root growth provides a greater surface area for colonisation to occur and may explain the higher percentage colonisation of the compost mulch in this site.

Nematode Study

In both sites and at both measured depths, the nematode populations fluctuated over the four seasons, ultimately decreasing in free-living and increasing substantially in plant parasitic nematode numbers in 2011. The favourable increase in free-living nematodes and decrease in plant parasitic nematodes from 2009 to 2010 was short lived as inverted outcomes occurred from 2010 to 2012. Nematodes react quickly to new resources (Storey and Hugo 2010). Changes in populations due to a soil amendment such as mulches are highly likely and may explain the fluctuations noted during the three seasons.

Root counts in 2010 were fairly poor in comparison to the following years. This may be an explanation to the decrease in plant parasitic/herbivorous nematodes which occurred in 2010 (data in Paper 4). Due to the accompanying increase in root growth with the use of organic mulches in 2011, herbivorous nematode populations were inclined to increase as more food was available (Storey and Hugo 2010). The increases in plant parasitic nematodes in the compost and woodchips treatments of the heavier soil site, and significantly higher

Trichoderma population (plant parasitic) as a result of the compost treatment in the lighter soil site, may be attributed to the high root count in these treatments and needs to be confirmed. With a high root count in the previous season, large amounts of food were available to a growing population and thus plant parasitic nematode populations were larger in the next season. In the following season (2012) root counts, particularly the woodchips treatment, were not as great as the other treatments. This may be as a result of the plant parasitic nematode populations in 2011.

In the heavier soil site, the woodchips treatment resulted in a significantly higher free-living nematode population in the 15 – 30 cm soil layer. This may be attributed to the potential increase in organic matter in the soil accompanied with the use of organic mulches, resulting in more food being made available to free-living nematodes, and thus encouraging their populations to increase.

Conclusion

As mycorrhiza colonization and nematode populations are very sensitive to changing soil environments (Storey and Hugo 2010), inconsistent trends due to the changing conditions brought about by the mulching materials are commonly reported (Kotze et al. 2012).The lack of similar trends between the two sites, as well as between the analysed mycorrizal and nematode populations in the different sites, indicates that the effects of mulching are dependent on the type of soil and focus area.

Changes in biological activity brought about by mulches are of a secondary nature. The increased biological activity in the organic treatments (favourable or unfavourable) can be attributed to increased organic matter and root volume as result of the organic mulches (data in Paper 4), which in turn resulted in a greater surface area for mycorrhizal colonization and more food for parasitic/herbivorous nematodes, i.e. compost. In contrast, the greater root volume also resulted in decreased mycorrhizal colonization in some instances, due to the roots no longer requiring assistance in nutrient uptake, which is adequate under these circumstances e.g. vermi-castings.

The compost treatment had consistently higher mycorrhiza colonization during three seasons in both sites, however, not always significantly higher than the other treatments. The vermi-castings treatment had consistently lower plant parasitic nematodes numbers. Higher free-living nematodes were also frequently noted over a period of four seasons for both sites. The organic mulches therefore proved promising results with regard to soil biota. Nevertheless, the period of the trial was not sufficient to produce consistent trends for both sites and all treatments. The contribution of over irrigation experienced for both sites could have also contributed towards final recommendations regarding application of mulches and the interaction with soil biota. Finally, the advantages of an increase in beneficial soil organisms needs to be quantified in terms of yield or fruit quality to motivate commercial producers to investigate this issue in future.

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Table 1. Percentage roots colonized by mycorrhizae in the heavier soil site in April of three seasons

	% Colonization		
Treatment	**2010**	**2011**	**2012**
Compost	90.00[ns]	77.5[A]	92.50[a]
Control	81.67	70[AB]	85.00[ab]
Geotextile Fabric	90.00	80[A]	65.00[cb]
Vermi-castings	85.00	40[B]	60.00[c]
Woodchips	98.33	57.50[AB]	77.50[abc]
p-value	0.4389	0.0857	0.0466
LSD	18.75	31.228	22.808

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 2. Percentage roots colonized by mycorrhizae in the lighter soil site in April of three seasons

	% Colonization		
Treatment	**2010**	**2011**	**2012**
Compost	95.00[a]	80[a]	57.50[ns]
Control	75.00[b]	42.5[c]	77.50
Geotextile Fabric	88.33[a]	52.5[bc]	75.00
Vermi-castings	91.64[a]	67.5[ab]	72.50
Woodchips	96.67[a]	65[ab]	72.50
p-value	0.0016	0.0121	0.6127
LSD	9.98	19.67	29.028

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

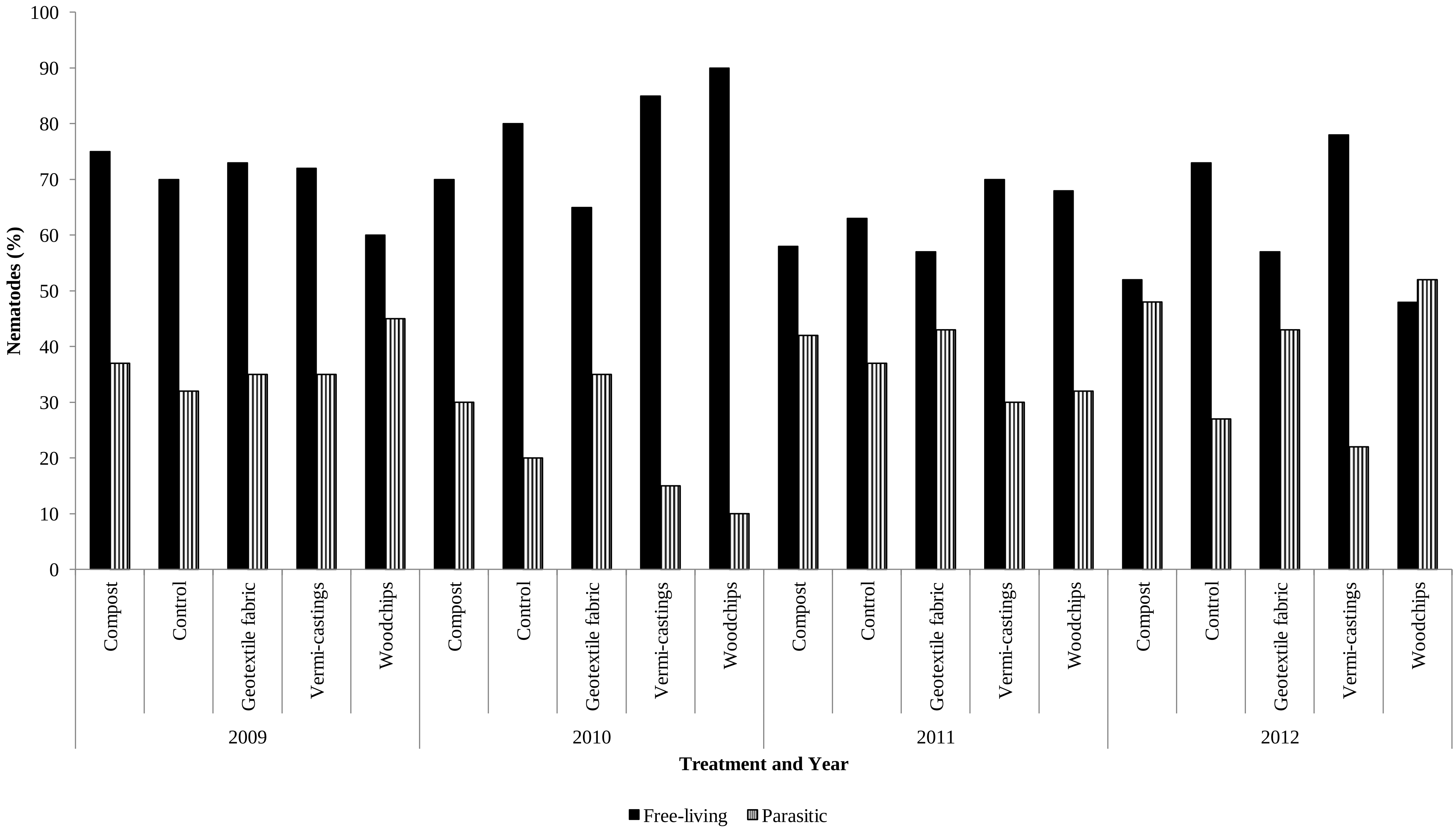

Fig. 1. Percentage nematode trend over three seasons, showing free-living and plant parasitic nematodes in the 0 – 15 cm soil layer in the heavier soil site

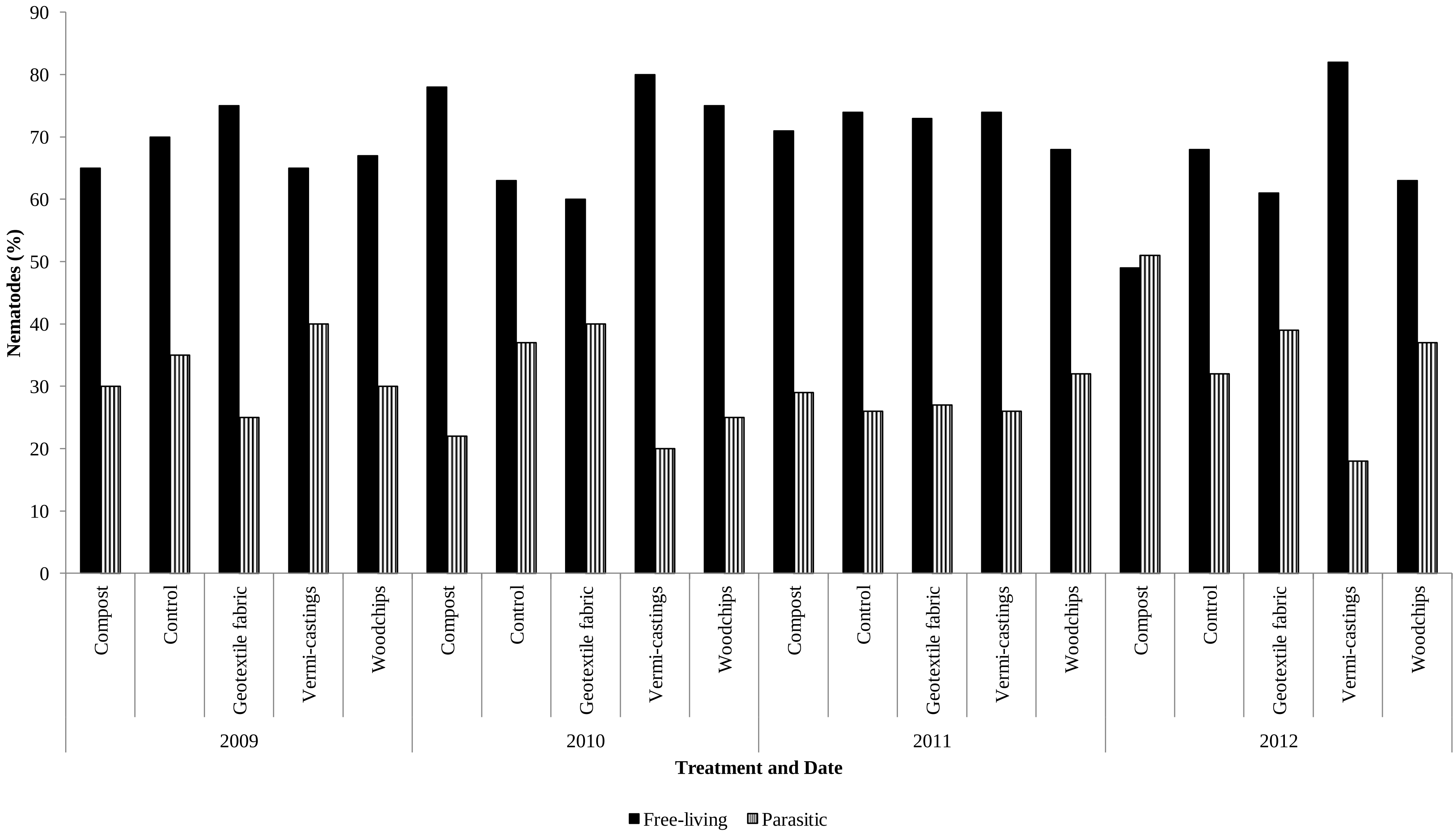

Fig. 2. Percentage nematode trend over three seasons, showing free-living and plant parasitic nematodes in the 0 – 15 cm soil layer in the lighter soil site

Table 3. Number of free-living and plant parasitic nematodes per 250 cm^3 soil from the 0 – 15 cm soil layer in the heavier soil site in April 2011 and 2012

	2011					2012				
Treatment	**Free-living**	**Parasitic**	**Pratylenchus**	**Xiphinema**	**Trichoderma**	**Free-living**	**Parasitic**	**Pratylenchus**	**Xiphinema**	**Trichoderma**
Compost	841.70^{ns}	610.00^{ns}	36.67^{ns}	543.30^{ns}	30.00^{ns}	678.30^{ns}	237.00^{ns}	15.00^{ns}	531.70^{ns}	80.00^{ns}
Control	670.00	395.00	15.000	300.00	80.00	818.30	600.00	33.33	141.70	61.67
Geotextile Fabric	515.00	386.70	48.33	543.30	30.00	745.00	422.00	38.33	531.70	30.00
Vermi-castings	685.00	300.00	3.33	258.30	38.33	963.30	627.00	10.00	200.00	31.67
Woodchips	665.00	320.00	26.67	236.70	56.67	710.00	242.00	55.00	318.30	48.33
p-value	0.2463	0.5801	0.2487	0.6031	0.4920	0.2755	0.7352	0.1064	0.7560	0.3358
LSD	280.92	424.35	42.981	435.45	67.263	284.63	780.68	36.31	782.69	56.381

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 4. Number of free-living and plant parasitic nematodes per 250 cm^3 soil from the 0 – 15 cm soil layer in the lighter soil site in April 2011 and 2012

	2011					2012				
Treatment	**Free-living**	**Parasitic**	**Pratylenchus**	**Xiphinema**	**Trichoderma**	**Free-living**	**Parasitic**	**Pratylenchus**	**Xiphinema**	**Trichoderma**
Compost	1068.30^{a}	230.00^{ns}	11.67^{ns}	188.30^{ns}	30.00^{ns}	653.00^{ns}	192.00^{ns}	28.00^{ns}	118.00^{ns}	45.00^{a}
Control	686.70^{b}	256.70	33.30	193.30	30.00	740.00	143.00	12.00	117.00	15.00^{b}
Geotextile Fabric	641.70^{b}	385.00	31.67	283.30	70.00	675.00	103.00	7.00	77.00	20.00^{b}
Vermi-castings	931.70^{ab}	235.00	28.33	183.30	23.33	703.00	102.00	18.00	77.00	6.6670^{b}
Woodchips	605.00^{b}	390.00	8.33	331.70	50.00	945.00	58.00	5.00	40.00	13.33^{b}
p-value	0.033	0.6919	0.499	0.7802	0.1551	0.319	0.2764	0.6394	0.6264	0.0082
LSD	331.72	318.82	37.198	301.42	41.429	303.5	126.16	35.167	118.65	20.236

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

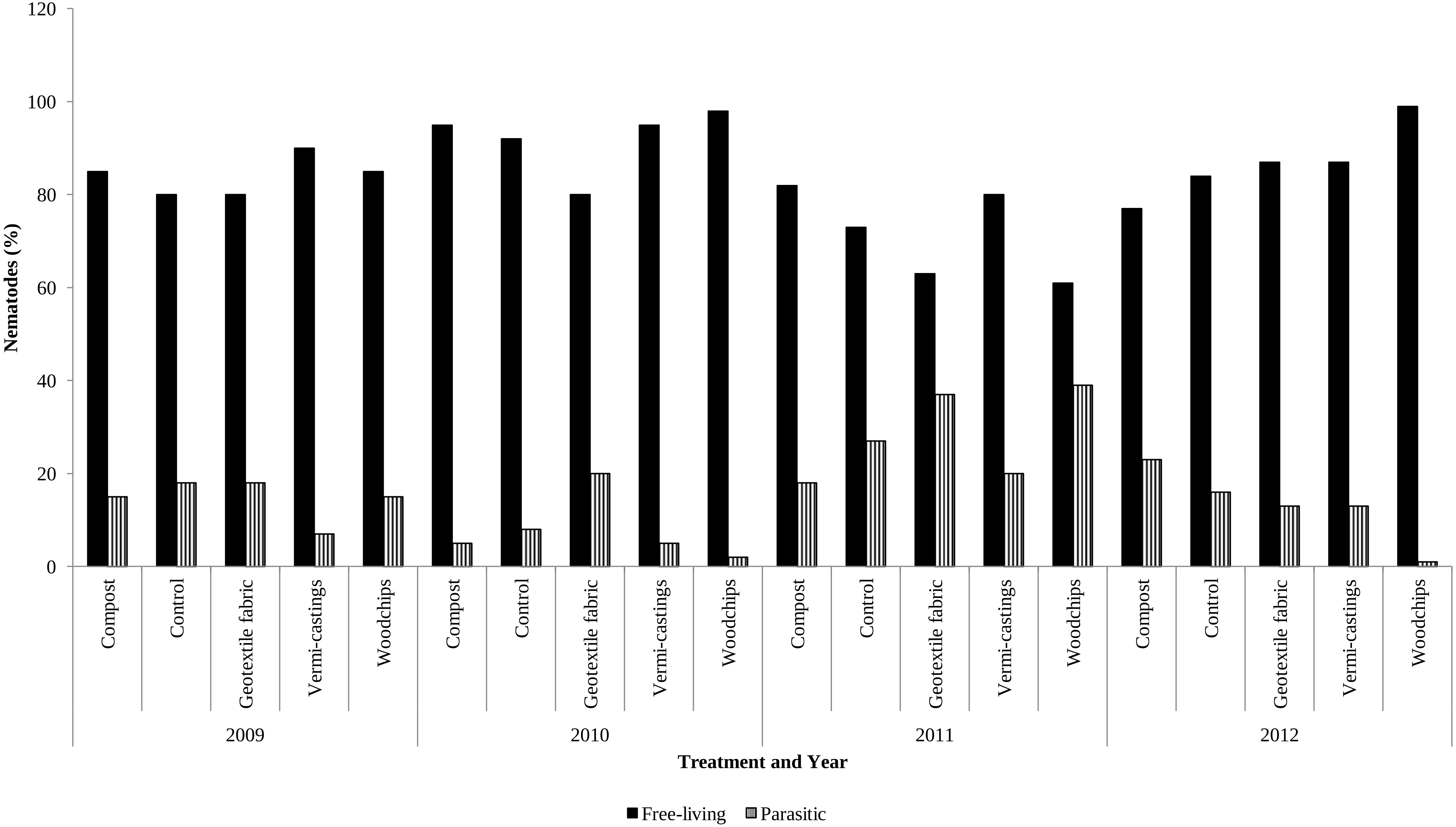

Fig. 3. Percentage nematode trend over three seasons, showing free-living and plant parasitic nematodes in the 15 – 30 cm soil layer in the heavier soil site

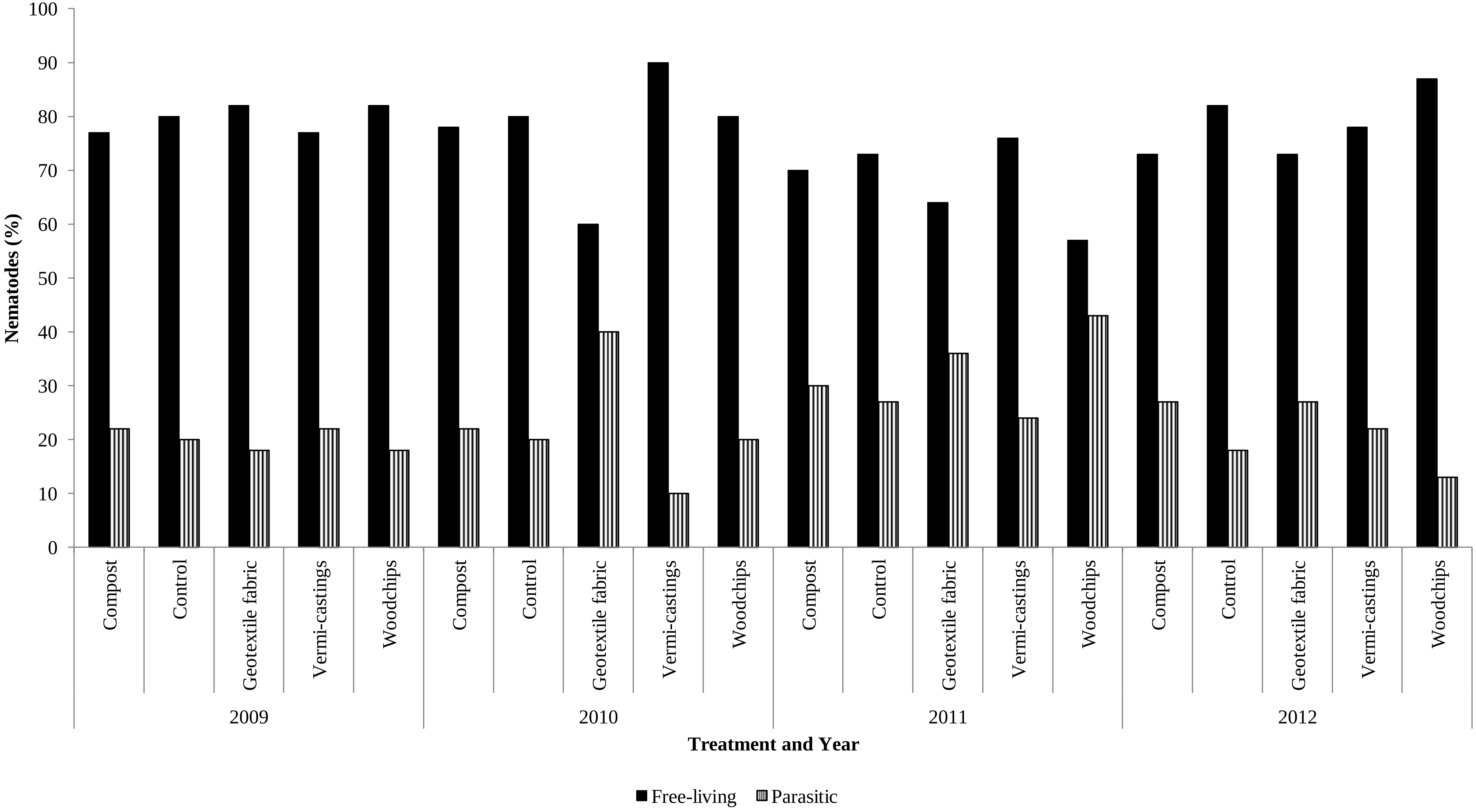

Fig. 4. Percentage nematode trend over three seasons, showing free-living and plant parasitic nematodes in the 15 – 30 cm soil layer in the lighter soil site

Table 5. Number of free-living and plant parasitic nematodes per 250 cm^3 soil from the 15 – 30 cm soil layer in the heavier soil site in April 2011 and 2012

	2011					2012				
Treatment	**Free-living**	**Parasitic**	**Pratylenchus**	**Xiphinema**	**Trichoderma**	**Free-living**	**Parasitic**	**Pratylenchus**	**Xiphinema**	**Trichoderma**
Compost	505.00^{ns}	206.67^{ns}	46.67^{ns}	98.33^{ns}	61.67^{ns}	550.00^{B}	573.00^{ns}	40.00^{ns}	498.00^{ns}	35.00^{AB}
Control	738.30	260.00	30.00	118.33	111.67	653.00^{AB}	307.00	27.00	170.00	110.00^{A}
Geotextile Fabric	581.70	220.00	50.00	140.00	30.00	560.00^{B}	352.00	33.00	282.00	37.00^{B}
Vermi-castings	590.00	205.00	25.00	91.67	88.33	872.00^{B}	193.00	10.00	132.00	52.00^{B}
Woodchips	568.30	261.67	23.33	148.33	90.00	588.00^{A}	339.00	36.00	243.00	58.00^{B}
p-value	0.2842	0.8846	0.7997	0.6848	0.1139	0.0837	0.7305	0.3663	0.7065	0.072
LSD	217.67	155.71	57.498	96.882	63.358	253.28	572.12	32.82	573.54	56.535

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 6. Number of free-living and plant parasitic nematodes per 250 cm^3 soil from the 15 – 30 cm soil layer in the lighter soil site in April 2011 and 2012

	2011					2012				
Treatment	**Free-living**	**Parasitic**	**Pratylenchus**	**Xiphinema**	**Trichoderma**	**Free-living**	**Parasitic**	**Pratylenchus**	**Xiphinema**	**Trichoderma**
Compost	803.30^{ns}	348.30^{ns}	11.67^{ns}	225.00^{ns}	111.67^{ns}	607.00^{ns}	227.00^{ns}	10.00^{ns}	150.00^{ns}	67.00^{ns}
Control	523.30	193.30	5.00	133.30	55.00	707.00	157.00	7.00	93.00	57.00
Geotextile Fabric	868.30	490.00	25.00	385.00	80.00	678.00	250.00	15.00	123.00	112.00
Vermi-castings	778.30	248.30	26.67	175.00	46.67	628.00	175.00	35.00	105.00	35.00
Woodchips	636.70	471.10	10.00	400.00	61.67	755.00	108.00	12.00	63.00	33.00
p-value	0.5595	0.4449	0.3705	0.5014	0.4124	0.6649	0.418	0.4941	0.7379	0.2771
LSD	470.38	398.89	26.686	387.16	74.814	226.84	164.28	35.297	135.75	80.053

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Paper 4

Quantifying changes in root number, size and distribution of 'Cripps' Pink' apple trees, after application of different mulches, and the resulting effect on fruit yield and sunburn.

Introduction

The basis of efficient, productive fruit producing orchards begins at the level of the root. The root environment is highly variable between areas and seasons and due to the ever changing characteristics of the soil (Giulivo 1990). The optimal aquisition and use of resources is vital in maintaining the correct balance of growth and development between roots, shoots and fruiting in orchards (Giulivo 1990), and these resources are ever changing in space and time (Forde and Lorenzo 2001). Water and nutrient uptake is not limited to white, newly produced roots, however, they are responsible for the majority of uptake (Atkinson 1983). Older roots can also access these resources and therefore uptake is not necessarily limited to root age (Wilson 1974; Atkinson and Wilson 1980). Physical, chemical and biological factors of the soil form integral parts in determining root growth, development and architecture. The tree's performance relies considerably on root systems that are well developed, efficient and flexible to adapt to changing soil environments, in order to overcome possible limitations in their habitat (Giulivo 1990; Forde and Lorenzo 2001). Soil properties must therefore be conducive in order for the tree to create such a root system.

The primary functions of any root system are anchoring and acquisition and transporting of nutrients and water from the medium in which they are grown to the shoots (Giulivo 1990; Bingham and Robinson 2003). Additionally, roots supply hormones to the rest of the plant and are important sinks for carbohydrates synthesised by the plant during photosynthesis (Aung 1974). Optimal root growth and development is therefore essential for good plant growth and production of fruit trees, and the medium in which the roots grow must be beneficial in this regard. Although the growth and development of root systems is essentially controlled genetically and by the amount of assimilates supplied by the canopy (Giulivo 1990), environmental factors also play an important role. Soil and groundcover management techniques can greatly improve the nature of the soil, which may result in enhancement of root growth and development and, ultimately, an improvement in health and quality of the orchard (Tisdall 1989).

Due to the increasing drive to preserve the deteriorating environment, many fruit growers are leaning towards integrated fruit production techniques in an effort to reduce environmentally damaging inputs (Merwin et al. 1995; Neilsen et al. 2004; Treder et al. 2004). Mulching has proved to be advantageous in developing and improving root systems, without adversely impacting the environment, and can play a fundamental role in integrated fruit production (Merwin et al. 1995; Neilsen et al. 2004; Treder et al. 2004).

In South Africa, periods of insufficient precipitation and rising temperatures are important limiting factors in crop production (Verdoodt et al. 2003). Nielsen (1974) reports that water availability and temperature are the primary climatic factors determining geographic plant distribution. With this in mind, as well as the effects of the changing environment, existing orchards may be at risk of reduced production and quality. Reduced soil water decreases root uptake of water and nutrients and thus adversely affects fruit yield and quality (Treder et al. 2004). In addition, extreme soil temperatures have been recorded in areas of crop production and can limit root growth or even kill existing roots (Tisdall 1989). Mulches are well known for their water conservation and temperature buffering properties (Treder et al. 2004; Varga et al. 2004; Nagy et al. 2008). On the other end of the spectrum, effects of excess water in the soil may be worsened by retarding evaporative losses with the use of mulches. Mulch performance is therefore reliant on environmental conditions and managerial practices. In addition to water and temperature amelioration, the extended use of mulches was shown to have positive effects on the nutritional and biological status of the soil (Nagy et al. 2008). Certain mulches add nutritional value to the soil, as well as promoting healthy microorganism populations that are beneficial to the root environment (Lakatos et al. 2001). Mulches can also alter soil physical properties and aeration (Haynes 1980) which, in turn, influence all of the above mentioned factors.

Amidst any soil cultivation technique, comes augmented or diminished weed populations (Fourie et al. 2011). Priority should be given to environmentally non-invasive cultivation practises in order to conserve the environment whilst still reaching the industry requirements, in terms of fruit production and quality (Cross et al. 1993). Certain mulching materials, particularly black inorganic and un-rotted organic materials, have proved to be beneficial in reducing weed populations and thus herbicide applications (Cross et al. 1993; Fourie et al. 2011). Mulching has shown to significantly reduce weed seed germination, due to limiting light levels required for germination and can therefore, successfully contribute to an integrated weed control system (Janick 1986; Wolstenholme et al. 1996).

Fruit growers are constantly striving for increased yield and quality. If certain exporting industry standards are not met, entire shipments can be rejected, resulting in extensive losses to the grower (Lang et al. 2001; Szewczuk and Gudarowska 2004). Mulching has also been shown to be beneficial, not only with regards to yield, but also to quality features including size, colour, mass and maintenance of fruit quality during storage (Szewczuk and Gudarowska 2004).

The physical, chemical and biological properties of the soil contribute equally in creating a habitable, effective root environment and are all closely linked to one another. This study was proposed due to the lack of South African studies done on mulches and their effect on the root environment and resulting fruit quality of commercial perennial crops.

Materials and Methods

Trial Layout

The trail was carried out at Lourensford Estate, Somerset West, South Africa (-34° 2' 31.29", +18° 55' 16.20") and commenced in October 2008 (Kotze et al. 2012). The trial consisted of two ‘Cripps’ Pink’ apple orchards planted in 1998 on M793 rootstocks on two different soil types. One site was on a heavier soil (Clovelly) and the other, an adjacent orchard, on a lighter soil (Tukulu).

The trial layout was a randomized complete block design with 5 treatments, 6 blocks, repeated on the 2 sites. Two buffer trees were added between plots to differentiate clearly between each plot. Each plot comprised four trees.

Of the five treatments, three were mulches consisting of organic materials, one of an inorganic material and the remaining one was the control, with no mulch. The organic mulches were as follows: wood chips containing no initial significant nutrient levels and originating from various tree species (excluding pine as it is known to leach allelochemicals); compost, where the nutrient levels were determined and vermi-castings (also with determined nutrient composition) with wood chips placed on top to prevent loss of the castings due to rain or wind. The inorganic mulch was a black polytex PT110 woven geotextile fabric that allowed water and nutrients to penetrate the soil, but contained no nutrient levels itself. The control treatment was not mulched and was under clean cultivation, where weeds were controlled according to farm management.

Normal commercial practises were followed regarding orchard management, apart from the irrigation. In January 2011 every second 42 ℓ h^{-1} micro-jet was replaced with a 20 ℓ h^{-1} micro-jet, reducing the deliverance of water due to suspected over irrigation, which became evident from historical data (Kotze et al. 2012). In October 2011 it was decided to further reduce irrigation, based on data acquired from FruitLook satellites, which was only available from 2011 and illustrated a lack of evapotranspiration deficit in both sites (fruitlook.co.za) (data in Paper 1), and thus the deliverance was further reduced by replacing every 42 ℓ h^{-1} micro-jet in the trial with 20 ℓ h^{-1} micro-jet. Evapotranspiration deficit is a measure of plant water stress. Although under normal crop production condition, plant water stress is not usually favourable, due to the nature of the trial and the use of mulching which essentially is a water conservation tool, a certain amount of water stress was require in order to receive results with regard to the mulches. The change in irrigation volumes, however, did not result in water reductions to the extent that would inflict stress on the control plots. The only spikes in evapotranspiration deficit were noted in times of heat waves where ambient temperatures reached upper thirties. The irrigation scheduling was maintained by the farm manager at two hours, three times per week, however irregularities in the irrigation scheduling were found during visits to the sites on various occasions.

Application of Mulches

Organic mulches were reapplied every year from trial commencement in October (2009 – 2011) to maintain a thickness of approximately 5cm on the soil surface. The inorganic mulch treatment, black polytex PT110 woven geotextile fabric, remained from the commencement of the trial.

A total of 90 ℓ of compost and woodchips respectively were evenly dispersed over their respective treatments per block during each reapplication. A total of 60 ℓ of vermi-castings, topped with 30 ℓ of woodchips, were evenly dispersed per block for the vermi-castings treatment.

Application of Mulches

Organic mulches were reapplied every year in October, from trial commencement to maintain a mulch of approximately 5 cm on the soil surface. The inorganic mulch treatment, black polytex PT110 woven geotextile fabric, remained from the commencement of the trial.

A total of 90 L of compost and woodchips respectively were evenly dispersed over their respective treatments per block. A total of 60 L of vermi-castings, topped with 30 L of woodchips, were evenly dispersed per block for the vermi-castings treatment.

Irrigation Monitoring

Due to the inconsistent nature of the irrigation practices in the site, and the suspected over irrigation which resulted in the installation of sprinklers with lower delivery rate in 2011, monitoring of the irrigation in the site was required. This was done by the use of XNP Multi-jet Domestic Water Meter Plastic Body Flow Meters (Sensus Metering Systems, Balamanzi PTY LTD, South Africa) and FullStop^{TM} Wetting Front Detectors (WFD) (FullStop^{TM} Wetting Front Detectors, CSIRO Land and Water, Australia) which were installed at the end of 2011. These instruments were monitored on a weekly basis for two months (February – March), during the peak in evapotranspiration and irrigation.

One flow meter was installed per site and applications rates for individual sprinklers on a weekly basis were determined based on the number of sprinklers downstream of the water meter. The flow meter and WFDs were installed in the same row in each site.

Three WFDs were installed in one block, per treatment per site, at three depths (20, 40 and 60 cm depths). The depths of installation were recommended by FullStop^{TM} for micro-jet sprinkler irrigation and were a reflection of the root zone existing around the shallow WFDs (20 cm and 40 cm). The deepest WFDs reflected the drainage zone (60 cm). They were each installed 30 cm away from the sprinkler and detected the depth of infiltrating water for each respective depth as delivered by one micro-jet. Percolation of water from the root zone was reflected by the occasional indication that the intermediate WFD (40 cm) was set off (a flag raised as the wetting front passes the funnel). Over irrigation was evident when the deep WFD (60 cm) was set off as this reflects drainage and over watering.

Nitrate concentrations were determined from soil water samples collected in the reservoir of the WFDs. It was monitored during the same period as the irrigation was monitored

(February – March) and from the same WFD depths. Samples for analysis were extracted using a syringe. Nitrate analysis was performed with a RQflex 10 Reflectoquant® Reflectometer (Merck KGaA, Germany) and nitrate test- and batch- specific bar-code strips (Merck KGaA, Germany). Measurement results were then displayed in mg ℓ^{-1}.

Soil Water

Water in the soil is referred to as soil water in this paper and refers to the water fraction in the soil that is available for uptake.

Soil water was measured on a continuous hourly logging basis by DFM probes (DMF, Continuous logging Soil Moister Probe, DFM Software Solutions CC, South Africa). DFM probes were installed in September 2010 and due to financial constraints, they were installed in only one plot per site (Kotze et al. 2012).

Relative soil water (% DFM soil water content) was measured at every 10 cm by sensors in the probes that reached down to 60 cm. Calibrative line graphs were required in order to convert the DFM soil water readings into quantitative soil water content (volumetric soil water content). This was done by taking four sets of soil samples at different soil water levels, providing a great enough soil water range to make an accurate calibration with the corresponding DFM soil water readings. Sampling was therefore done during 'wet' and 'dry' cycles, when the soil was either just irrigated or after significant water depletion. Samples were taken with a 5 cm Thomson's auger. Sampling was done as close to the DFM probes as possible, without impacting DFM measurements (approximately 5 cm away from the probe), at 10 cm, 20 cm, 30 cm and 40 cm. Gravimetric soil water content was calculated (soil water in terms of mass represented by weight; product of mass and the gravitational acceleration), and then converted to volumetric soil water content (soil water in terms of volume). The samples were weighed in the laboratory to determine their total weight (A) and then oven dried for approximately twenty four hours at 105°C. They were then weighed again to determine the weight of solids (B). Gravimetric water content (w) was calculated according to Equation 1.

$$w\ (\%) = \frac{A-B}{B} \times 100 \qquad (1)$$

Gravimetric water content was converted to volumetric water content with the use of estimated, set bulk density (ρ_b) values (ρ_b = 1.4 for the heavier soil; ρ_b = 1.5 for the lighter soil). The volumetric water content (θ) was calculated according to Equation 2.

$$\theta\ (\%) = w\ \times \rho_b \qquad (2)$$

Root Study

Root studies were conducted in April 2010 (Kotze et al. 2012), 2011 and 2012 according to the methods of Böhm (1978). Due to the destructive nature of the study, only one replicate per treatment, per year, per site, was analysed. The method required a trench of 1.2 m deep and 1.3 m wide, dug 30 cm away from the tree into the row. The trench wall was smoothed with a spade and protruding roots were cut to the surface. Roots were exposed by removing 5 – 10 mm of soil surrounding the roots. The roots were then spray painted white to increase their visibility and areas of soil surrounding the painted roots, which were also exposed to paint, were carefully scraped away.

Roots were counted using a 100 cm x 100 cm wire grid with 10 cm x 10 cm blocks and 4 mm wire diameter. Roots were classified in terms of four diameter classes: <2 mm, 2 mm - 5 mm, 5 mm -10 mm and, >10 mm in each block, and then totalled in each depth interval down the profile.

Weed Study

Analyses of weeds in the trial was secondary to all of the other studies, and due to normal commercial weed control implemented by farm management, quantifying the weeds was challenging. As a result, only one weed study, quantifying summer weeds, could be completed during November 2011. Weeds were counted using photographs of four replicates per treatment, per site. The area included in the photographs comprised a 100 cm x 100 cm wire grid with 10 cm x 10 cm blocks, and number of weeds were counted in each block (100 blocks in total) and then totalled to give total weeds per area photographed.

Fruit Yield and Quality

Fruit were harvested during April and May each year, depending on time of fruit maturity determined by the farm manager, and multiple harvests were required due to the maturing and colouring qualities of 'Cripps' Pink' apples. Yield per plot was determined from fruit from all four trees per plot at each harvest. The total yield of each plot was then related to trunk circumference to determine the yield efficiency per treatment.

Two samples of 20 fruit, of similar size, per block per treatment, in both sites, were randomly selected each year at the main harvest for fruit quality analyses, by the Department of Horticulture, and mineral analyses, by a commercial laboratory (Bemlab Pty Ltd, Strand, South Africa). Another sample of 20 fruit was stored for two months under regular atmosphere at -0.5° C to determine storage quality. Fruit quality and mineral analyses were done annually from 2009 to 2012 according to standard procedure described by Kotze et al. (2012).

Sunburn incidence was evaluated at harvest as the proportion of fruit in the samples used for maturity indexing, mineral analyses and post storage evaluation which showed sunburn symptoms out of the total number of fruit (60 fruit). A 'Granny Smith' sunburn evaluation chart (Deciduous Fruit Board Set A33) was used to evaluate sunburn severity and expressed as a percentage, however, sunburn severity was not addressed in this paper.

Statistical Analysis

All data that was of a statistical nature was analyzed using the Statistical Analysing System (SAS) programme 9.1 (SAS Institute Inc, 2004, Cary, NC). Analyses of variances were analyzed using a General Linear Model (GLM) procedure and standard errors and least square means were calculated for each treatment. Data was considered significant at a 5% significance level and 10% significance level where specified.

Results

Irrigation Monitoring

Irrigation in the heavy slit loam site, recorded by the flow meter, was very inconsistent during the period in which it was monitored (1 February 2012 – 31 March 2012), and drastic increases in water application occurred during the first two weeks of March (Fig. 1, 2 and 3), which corresponded with an increase in temperature during this time (data in Paper 1). WFDs at all three depths in the geotextile fabric treatment were activated more readily than in the other treatments. This even occurred when irrigation was reduced during the beginning

(February) of the monitored period. WFDs in the vermi-castings treatment were also set off more frequently during the early period, however, not to the same extent as the geotextile fabric treatment. Only the 20 cm and 40 cm depth WFDs in the vermi-castings treatment were set off regularly (Fig. 1 and 2). The increase in irrigation during the first two weeks in March was accompanied by more frequent activations of the WFDs, at all three depths, in all treatments. The WFDs at the 40 cm and 60 cm depths of the control treatment were not set off as readily as in the other treatments (Fig. 2 and 3). Even with the decrease in irrigation in the last two weeks of March, most of the WFDs at the site continued to activate.

The lighter soil site was not exposed to the drastic increase in irrigation in March as the heavier soil site was, however, irregularities in irrigation also occurred in this site (Fig. 4, 5 and 6). In all treatments, most of the 20 cm WFDs were constantly set off during the period in which the irrigation was monitored (Fig. 4). The exceptions were most likely due to blockages in the sprinklers that were noted and rectified on subsequent orchard visits. The third week of February realized an increase in irrigation which resulted in the activation of more of the deeper WFDs, in the site, the week after the increase. From the final week in February to the end of March, the majority of the WFDs, at all three depths and treatments, were set off. In contrast to the activation of geotextile fabric and vermi-castings treatments WFDs which were noticeably more frequent in the heavier soil site, none of the treatments in the lighter soil site showed any clear trends in this regard.

The evapotranspiration deficit, according to FruitLook (fruitlook.co.za) satellite data for both sites, October 2011 to March 2012, clearly reflected over irrigation (very little evapotranspiration deficit) after week 2 (Fig. 7). Due to the water conservation properties of mulches, a certain amount of tree water stress was required in order to see differences between treatments. Figure 3 confirms that this was not accomplished.

In the heavier soil site, nitrate levels in the soil water samples increased with an increase in irrigation volume (Fig. 8). Levels were also consistently higher in the soil water samples from the control and vermi-castings treatments compared to the other treatments. After the drastic increase in irrigation volume in the beginning of March, nitrate levels in the soil water samples decreased somewhat in all of the treatments.

In the lighter soil site, nitrate levels in the soil water samples were considerably higher than in the heavier soil site (Fig. 9). Nitrate levels were consistently higher in the vermi-castings treatment compared to the other treatments. At the beginning of the period in which irrigation was monitored, the 20 cm WFD in the vermi-castings treatment reflected the highest nitrate concentrations. Over time, the 40 cm WFD in the vermi-castings treatment collected soil water samples with increasing nitrate levels, until irrigation was reduced in the last week of March, when nitrate levels in the 60 cm WFDs decreased. However, levels still remained considerably higher than the other treatments. After increased irrigation, the compost and geotextile fabric treatments also reflected higher nitrate levels in their soil water samples collected from the 60 cm WFDs.

Root Study

Historical root data from 2010, adapted from Kotze et al. (2012), was used along with data from 2011 and 2012 for the root study.

The total number of roots, particularly the fine roots, in the soil profile of both sites increased from 2010 to 2012 (Fig. 10 and 11). It must, however, be noted that root studies were performed on a new replicate each year and thus do not reflect growth in a specific block, but growth per treatment.

Heavier soil site

Dramatic increases in numbers of roots < 2 mm occurred from 2010 to 2011 in the heavier soil site (Fig. 10). Root numbers of the other diameter classifications did not increase as considerably in 2011, however, increases were noted. Root number trends differed from 2010 to 2011. The control treatment, followed by the compost treatment, resulted in the highest number of roots < 2 mm diameter (709 and 571 roots respectively), where as the woodchips treatment, followed by the vermi-castings treatment, resulted in the lowest number (316 and 353 roots respectively). It must be noted that some of the organic mulched treatments, particularly the woodchips and vermi-castings treatments, resulted in fine roots growing into the mulches and these were not taken into account. The control treatment, followed by the geotextile fabric treatment, resulted in the highest number of 2 – 5 mm diameter roots (56 and 48 roots respectively), whereas, the vermi-castings and woodchips treatments, subsequently resulted in the lowest number (22 and 24 roots respectively). The geotextile fabric treatment also resulted in the highest number of 5 – 10 mm diameter roots (19 roots). The woodchip treatment resulted in the lowest number of roots < 10 mm (2 roots). Differences in number of

5 – 10 mm diameter and > 10 mm diameter roots between the other treatments were marginal and similar to results in 2010 (Kotze et al. 2012).

In the heavier soil site from 2011 to 2012, the compost treatment, followed by the woodchips treatment, resulted in the highest number of roots < 2 mm diameter (800 and 730 roots respectively), whereas the geotextile and vermi-castings treatments resulted in the lowest number (432 and 566 roots respectively). The compost treatment resulted in a considerably higher number of 2 – 5 mm diameter and > 10 mm diameter roots (161 and 52 roots respectively). The other treatments did not differ much from each other in this regard, falling between 82 and 52 roots of the 2 – 5 mm diameter classification, and 28 and 13 roots of the 5 - 10 mm diameter classification. Differences in number of > 10 mm diameter roots between the other treatments were marginal.

With regards to the soil profile, root distribution in the compost treatment resulted in a bigger volume of roots < 2 mm diameter from 2010 to 2011, and even more in 2012 (Fig. 12). In 2010 the fine roots only stretched down to 40 cm depth in the profile. However, in 2011 and 2012 fine roots were found as deep as 80 cm in the profile. Larger diameter roots were also distributed more evenly from year to year. A bigger volume of roots in all four diameter classifications were present in the top 40 cm of the profile in 2012 compared to 2010 and 2011.

As with the compost treatment in this site, the control treatment also resulted in a bigger volume of roots < 2 mm diameter in 2011 and 2012, compared to 2010 (Fig. 13). However, the overall fine root distribution decreased from 2011 to 2012. In 2010, the majority of the fine roots occurred in the top 20 cm of the profile. In 2011, however, fine roots were counted as low as 100 cm in the profile. In 2012 the majority of the fine roots occurred in the top 50 cm of the profile. The distribution of the larger diameter roots remained fairly constant over the three years.

In the geotextile fabric treatment, fine root distribution increased from 2010 to 2011and 2012 (Fig. 14). Fine roots were fairly evenly distributed throughout the profile in 2011, reaching down to approximately 80 cm depth. The volume of roots at a depth of 80 cm, however, decreased from 2011 to 2012. More fine roots were concentrated in the top 20 cm of the profile in 2012, although fine roots were still counted deeper down the profile (80 cm depth). The larger diameter roots were also more evenly distributed in 2011 compared to 2010.

In the vermi-castings treatment, fine root distribution increased from 2010 to 2011and 2012 (Fig. 15). Overall root distribution remained relatively constant from 2011 to 2012, with the exception of the fine roots which became slightly more concentrated in the top 20 cm of the profile in 2012. Distribution of the roots > 10 cm also increased slightly from 2011 to 2012.

Overall root volume and distribution increased from 2010 to 2012 in the woodchips treatment (Fig. 16). Very few fine roots were counted deeper than 20 cm in 2010. In 2011, however, fine roots extended as deep as 80 cm and even deeper in 2012. Intermediate and larger diameter roots were also more evenly distributed from 2011 to 2012.

The relationships between soil temperature, %C and water in March and April, and number of fine roots in the heavier soil site were investigated (Fig. 22, 23 and 24). The roots were counted towards the end of April and thus the soil water and temperatures before this time were relevant for interpretation. Correlations were done to investigate the relationship between these parameters and roots growth. With low R^2 numbers as a result of all three of the parameters (soil temperature $R^2 = 0.0094$, % C $R^2 = 0.0189$, soil water $R^2 = 0.5218$), it is evident that no single factor is entirely responsible for manipulating root growth. Soil water had the highest R^2 number and thus was the most influential and resulted in an inverse linear relationship, where with a decrease in soil water, an increase in fine roots occurred. The control and compost treatments resulted in the highest root counts over the two years. These treatments also resulted in lower soil water percentages. It is however evident that the soil temperature and %C did play a role in manipulating fine root growth.

Lighter soil site

In the lighter soil site in 2010, the geotextile fabric and woodchips treatments resulted in the highest number of roots of all of the respective root diameter classifications (280 and 269 respective roots < 2 mm diameter; 51 and 54 respective roots of the 2 – 5 mm diameter; 20 and 13 respective roots of the 5 – 10 mm diameter and 13 respective roots > 10 mm diameter). However, treatments only differed marginally in the number of roots, with the exception of the 5 – 10 mm diameter classification (Fig. 11).

In 2011, the control treatment was the only treatment that resulted in a notable increase in the number of roots < 2 mm. As in the heavier soil site, fine root grew into the organic mulched treatments, particularly the woodchips and vermi-castings treatments, in the lighter soil site. The control treatment, followed by the compost treatment, had the highest number of roots <

2 mm diameter (462 and 320 roots respectively), where as the woodchips treatment resulted in the lowest number (173 roots). The vermi-castings treatment resulted in the highest number of 2 – 5 mm diameter roots (85 roots). The other treatments did not differ greatly from each other in this regard. The geotextile fabric treatment resulted in the lowest number of 5 – 10 mm diameter roots (1 root) and the compost treatments resulted in the lowest number of roots > 10 mm diameter (2). As with the 2 – 5 mm diameter classification, the other treatments did not differ greatly from each other with regards to the larger diameter root groupings.

Greater increases in root numbers in all of the diameter classifications, with the exception of the > 10 mm classification, were noted from 2011 to 2012, compared to 2010 to 2011. The geotextile fabric treatment, followed by the woodchips treatment, resulted in the highest number of roots < 2 mm diameter (926 and 895 roots respectively), 2 – 5 mm diameter (154 and 149 roots respectively) and 5 – 10 mm diameter (32 and 26 roots respectively). The control and compost treatments resulted in the lowest number of roots < 2 mm diameter (366 and 735 roots respectively), 2 – 5 mm diameter (112 and 69 roots respectively) and 5 – 10 mm diameter (17 and 11 roots respectively). The control treatment also resulted in the lowest number of roots > 10 mm diameter (3 roots). The other treatments did not differ greatly from each other in this regard.

Overall root distribution in the lighter soil site was superior to that of the heavier soil site in all of the treatments over the three years. Fine and intermediate roots extended to greater depths in the lighter soil site compared to the heavier soil site.

In the compost treatment, fine root distribution and volume increased slightly from 2010 to 2011 and 2012 (Fig. 17). In 2010, fine roots reached 80 cm down the profile, where as in 2011 and 2012 they reached further (100 cm). In 2011 and 2012, a bigger volume of fine and intermediate roots occurred in the top 20 cm of the profile, compared to what was found in 2010. Fine and intermediate roots also increased in volume in the bottom 20 cm of the profile in 2011, breaking the distribution slightly from top to bottom of the profile. This can partly be attributed to a limiting layer that was observed to the one side of the soil profile. Larger diameter root distribution and volume remained fairly constant from 2010 to 2012.

Fairly irregular root distribution was found in all three years of the control treatment (Fig. 18). Bigger volumes of fine and intermediate roots were found closer to the surface and then deeper in the profile (60 cm), leaving a fairly unoccupied gap in the middle of the profile.

This was consistent from 2010 to 2012, however, root volume increased, and to greater depths in the profile during this period. Intermediate root volume increased from 2011 to 2012, whereas fine and large roots decreased.

In the geotextile fabric treatment, fine roots became wider distributed through the profile from 2010 to 2011, however, roots numbers did not increase (Fig. 19). Fine roots therefore became less concentrated near the surface, and more spread out through the profile. In 2012 root distribution remained constant from 2011, however, fine and intermediate root number increased dramatically which resulted in a greater volume of roots distributed throughout the profile. Roots of diameters 5 – 10 mm and > 10 mm remained fairly constant with regards to volume and distribution from 2010 to 2012.

Fairly irregular root distribution was found in 2010 as a result of the vermi-castings treatment (Fig. 20). Root volume and distribution increased in 2011 and 2012, and bigger volume of fine and intermediate roots were found to greater depths in the profile (100 cm versus 80 cm). In 2012 more fine roots concentrated in the top 20 cm of the profile, however, roots remained well distributed. Roots of diameters 5 – 10 mm and > 10 mm also increased in distribution in 2012.

Overall root volume and distribution remained fairly constant from 2010 to 2011 in the woodchips treatment, with the exception of fine roots extending into the mulch in 2011 (Fig. 21). In 2012, however, fine root volume and distribution increased dramatically and became more concentrated in the top 20 cm of the profile as well as extending to deeper areas of the profile. Intermediate and large roots also occurred in healthy numbers in the top layers of the profile. Overall root occurrence was therefore well dispersed throughout the profile.

The relationships between soil temperature, %C and water in March and April, and number of fine roots in the lighter soil site are illustrated in Figures 25, 26 and 27). The R^2 values, as a result of three of the parameters, were higher in the lighter soil compared to the heavier soil (soil temperature R^2 = 0.15123, % C R^2 = 0.6101, soil water R^2 = 0.478), and thus is evident that all three of the parameters played more of a role in manipulating root growth. Percentage C resulted in the highest R^2 value and thus had the best linear relationship. Considering the lighter texture of the soil, soil water was not as influential as it was in the heavier soil, however it also resulted in an inverse linear relationship, where with a decrease in soil water, an increase in fine roots occurred. All of the mulched treatments resulted in the highest root counts over the two years, and their influence became more pronounced in 2012 with less water in the profile.

Weed Study

The weeds found in the weed study in both sites were primarily *Cyperus rotundus* (red nutgrass) which are perennial weeds that are commonly found in orchards (Reinhart et al. 2000). In both sites the geotextile fabric treatment performed the best with regards to suppressing weeds, resulting in up to 65% less weeds in the heavier soil site, and 10% less weed in the lighter soil site (Fig. 28 and 29). The greatest differenced was therefore found in the heavier soil site, as well as significant differences between treatments (P = 0.0062). The geotextile fabric resulted in a significantly lower percentage weeds (2.25%) compared to the other treatments (ranging from 67.5% to 38.75%), which did not differ significantly from each other (Fig. 28). No significant differences were found between treatments in the lighter soil site (Fig. 29).

In the heavier soil site, the control treatment performed on par with the woodchips and compost treatments, whereas in the lighter soil site, the woodchips and vermi-castings treatments performed better than the control treatment.

Fruit Yield and Quality

Few significant differences between treatments in both sites were found over the duration of the trial with regards to fruit yield and quality (Makeredza 2011; Kotze et al. 2012; v.d. Merwe 2012). For this reason, only the yield efficacy and sunburn data will be discussed in this paper (Fig. 30 – 33). The other fruit yield and quality data can be found in Kotze et al. (2012) and v.d. Merwe (2012). Historical data from 2009 and 2010, adapted from Kotze et al. (2012) with regards to the yield efficiency, and Makeredza (2011) with regards to the sunburn, was used along with data from 2011 and 2012 adapted from v.d. Merwe (2012). Significant differences between treatments were also found with regards to the phosphorus (P) content in the fruit mineral analysis of the heavier soil site in 2011, and the boron (B) content in the fruit mineral analysis of the lighter soil site in 2011 (in v.d. Merwe 2012, data unpublished).

In both sites yield efficiency decreased substantially from 2009 to 2010, when it reached a plateau which was maintained until 2012 (Fig. 30 and 31).

In the heavier soil site, significant differences between treatments occurred during the four years of the trial (Fig. 30). In 2009, the woodchips treatment resulted in the highest yield efficiency (1.52 kg/cm), and differed significantly from the control and compost treatments (1.20 kg/cm and 1.08 kg/cm respectively) (P = 0.0293). The geotextile fabric and vermi-castings treatments did not differ significantly from any of the treatments in this year. In 2010, the control, vermi-castings and woodchips treatments resulted in the highest yield efficiency (0.75 kg/cm, 0.72 kg/cm and 0.75 kg/cm respectively) and differed significantly from the geotextile fabric and compost treatments (0.57 kg/cm and 0.45 kg/cm respectively) (P = 0.002). In 2011, the vermi-castings treatment resulted in the highest yield efficiency (0.65 kg/cm) and differed significantly from the compost, control and geotextile fabric treatments (0.45 kg/cm, 0.45 kg/cm and 0.44 kg/cm respectively) (P = 0.0491). The woodchips treatment did not differ significantly from any of the treatments. In 2012, the woodchips and vermi-castings treatments resulted in the highest yield efficiency (0.73 kg/cm and 0.72 kg/cm respectively), and differed significantly from the geotextile fabric and compost treatments (0.54 kg/cm and 0.5 kg/cm respectively) (P = 0.0284). No significant differences were found between the former and latter two treatments. The control treatment did not differ significantly from the woodchips, compost and geotextile fabric treatments, however, it did differ from the compost treatment, which realised the lowest yield efficiency.

In contrast to the heavier soil site, no significant differences were found between treatments with regard to the yield efficiency in any of the four years in which the trial commenced in the lighter soil site (Fig. 31).

In both sites the incidence of sunburn at harvest was at its lowest in 2010 (1.7 - 3.8% in the heavier soil site; 3 - 5% in the lighter soil site) and highest in 2011 (14.17 - 20.83% in the heavier soil site; 21.67 - 27.5% in the lighter soil site) (Fig. 32 and 33).

In the heavier soil site, significant differences between treatments were only found in 2010, where the control treatment resulted in significantly higher sunburn than the other treatments, with exception of the compost treatment (P = 0.001)(Fig. 32). In 2009 and 2010, the control treatment resulted in the highest incidence of sunburn, and the geotextile fabric treatment the lowest. In 2011 and 2012, however, the compost treatment resulted in the highest incidence of sunburn, and the control treatment the lowest in 2011 and the geotextile fabric treatment the lowest in 2012.

In the lighter soil site, significant differences between treatments were found in 2009 and 2010 ($P = 0.0254$ and $P = 0.045$ respectively), but not 2011 and 2012. In 2009, the control treatment resulted in the highest incidence of sunburn (11.3%) and differed significantly from the geotextile fabric and vermi-castings treatments (6.7% and 4.3% respectively), which did not differ significantly from each other and resulted in the lowest incidence of sunburn (Fig. 33). The woodchips treatment was significantly higher than the vermi-castings treatment, but not from the compost treatment, which did not differ significantly from any of the treatments. In 2010, the control resulted in the highest incidence of sunburn again (5.0%), and differed significantly from the other treatments. The control treatment resulted in a consistently higher incidence of sunburn during the four years. The vermi-castings treatment resulted in the lowest incidence of sunburn in 2009 and 2010, and the woodchips treatment resulted in the lowest incidence in 2012.

Fruit N, P and K contents were addressed in this paper from 2009 and 2012 to show the change over time, as these nutrients are commonly added to the soil and can be greatly affected by properties in the soil (Tisdall 1989; Forde and Lorenzo 2001; Kotzé 2001) (Table 2 and 3). They are also vital for fruit quality (Bramlage et al. 1980; Kotzé 2001).

In the heavier soil site, no significant differences between treatments were found with regard to the fruit N, P and K contents in 2009 and 2012 (Table 2). In 2009, the control treatment resulted in the highest N content compared to the other treatments. In 2012, however, the vermi-castings and compost treatments resulted in the highest N contents with increases of 8 mg 100 g^{-1} and 7.17 mg 100 g^{-1} respectively from 2009 to 2012. They were followed by the woodchips treatment which realised an increase of 8.34 mg 100 g^{-1}. The geotexile fabric treatment realised an increase of 5 mg 100 g^{-1}, where as the control treatments only realised an increase of 2.83 mg 100 g^{-1}. In 2009 the vermi-castings treatment resulted in the highest fruit P and K contents. In 2012, however, it was surpassed by the compost treatment. The vermi-castings and compost treatments realised increases of 1.29 mg 100 g^{-1} and 4.7 mg 100 g^{-1} respectively, with regard to the P content. With regard to the K content, however, the vermi-castings realised a decrease of 4.5 mg 100 g^{-1}, and the compost realised a considerable increase of 24.67 mg 100 g^{-1}. These treatments continued to produce considerably higher P and K contents in 2012.

In the lighter soil site, significant differences between treatments were found with regard to fruit P content in 2012 ($P = 0.0134$) (Table 3). In 2011 the woodchips treatment resulted in the highest P content. In 2012, however, the vermi-castings treatment resulted in the highest P content (6.16 mg 100 g^{-1}) and was significantly different to the compost, geotextile fabric and control treatments (9.13 mg 100 g^{-1}, 9.11 mg 100 g^{-1} and 6.16 mg 100 g^{-1} respectively), which did not differ significantly from each other. The vermi-castings treatment realised a considerable increase of 7.29 mg 100 g^{-1} from 2009 to 2012. The woodchips treatment did not differ significantly from any of the treatments (9.55 mg 100 g^{-1}) and realised an increase of 2.91 mg 100 g^{-1} from 2009 to 2012. In 2009 the woodchips and compost treatments resulted in the highest fruit N content, and realised increases of 14.34 mg 100 g^{-1} and 11.17 mg 100 g^{-1} respectively from 2009 to 2012. In 2012, however, the geotextile fabric and vermi-castings treatments resulted in the highest N contents, and realised increases of 19.16 mg 100 g^{-1} and 16.83 mg 100 g^{-1} respectively from 2009 to 2012. In 2009 the compost and woodchips treatments resulted in the highest K contents. However, in 2012, the vermi-castings and compost treatments resulted in the highest K contents and realised increases of 27 mg 100 g^{-1} and 4 mg 100 g^{-1} respectively from 2009 to 2012.

Discussion

Irrigation Monitoring

In both sites, increased irrigation was accompanied by increased activation of the WFDs and to greater depths. With increased soil wetness, quicker activation of the WFDs resulted. This corresponds with reports by Stirzaker (2003) and Fessehazion et al. (2011) about WFDs. The WFDs in the lighter soil site were more readily set off compared to the heavier soil site. This is due to the water moving quicker down the profile in the lighter textured soil compared to the heavier textured soil, confirming reports by Stirzaker (2003) and Fessehazion et al. (2011). More water was retained in the upper centimetres of the heavier soil; and thus did not travel down the profile in order to set off the WFDs. However, the drastic increase in irrigation in the heavier soil site in the beginning of March and thereafter, evident from the flow meters, was accompanied by more activation of the WFDs. This can be attributed to increased profile wetness, resulting in more water drainage, even after irrigation had decreased again.

In the beginning of the period in which irrigation was monitored, only the shallow WFDs were consistently set off in the lighter soil site and to a lesser extent in the heavier soil site.

This confirms that irrigation scheduling during this period was more optimal and reduced leaching, as water remained in the root zone and drainage was limited. It is also evident from the FruitLook and flow meter data combined (Fig. 7), that the plants were transpiring effectively, as evapotranspiration peaked at that point. Irrigation scheduling was thus well managed at the beginning of March, considering the increase in temperature that occured (data in Paper 1), and the plants were therefore functioning effectively with regard to transpiration requirements. As irrigation continued during the period in which it was monitored, it became increasingly evident that over irrigation was occurring, and the decreasing temperatures (data in Paper 1) were not accounted for by a decrease in irrigation (Fig. 7). More activation of the deeper WFDs in both sites occurred and was accompanied by the no peaks in evapotranspiration deficit. This indicated that too much water was being applied and drainage was occurring out of the root zone in both sites, during this period (Stirzaker 2003; Fessehazion et al. 2011). In addition, nitrate levels decreased in the soil water after increased irrigation. Nitrate is prone to leaching (Maynard 1989) and therefore the decrease in nitrate levels after excessive irrigation is evidence that leaching was taking place. The available nitrate in the soil was consequently being washed out of the root zone and if this continues, a reduction in vegetative growth results.

In the heavier soil site all of the WFDs of the geotextile fabric treatment and particularly the shallow WFDs of the vermi-castings treatment, were consistently activated throughout the period in which irrigation was monitored. This can be attributed to the higher soil water content that was measured in these treatments (data in Paper 1), which allowed for more free water in the soil to drain into deeper parts of the profile, and thus increased nitrate leaching.

The majority of nitrate in the soil and thus the soil water extracted from the WFDs, originated from the Triton fertilizer application, six weeks after full bloom (2011/12/28) (Table 1), which contained 16.5% N. Nitrate levels were consistently higher in the soil water samples from the control and vermi-castings treatments in the heavier soil site and from the vermi-castings treatment in the lighter soil site. The higher nitrate levels from the vermi-castings treatment can be attributed to the release of additional nitrogen from the actual mulching material. Nitrogen levels in the vermi-castings mulching material were found to be considerably higher compared to the other organic mulching materials before application (data in Paper 2). After a growing season, nitrogen levels in the residual mulch decreased substantially in the vermi-castings mulching material (data in Paper 2), and thus provide evidence that the higher nitrate in the soil solution of the vermi-castings treatments, compared to the other treatments, most likely originated from the mulching material. The other organic mulching materials, however, did not result in markedly higher nitrate levels in the soil solution compared to the other treatments, which could be due to the decomposition process of the mulches themselves or to less nitrogen in the mulching material. The higher nitrate levels in the control treatment at the heavier soil site, compared to the other treatments, may be attributed to the poorer physical conditions of the control treatment (data in Paper 1), and therefore more leaching.

When nitrogen is released due to decomposition, it is in the form of ammonium (Maynard 1989; Taiz and Zeiger 2010). Ammonium is either taken up by the roots, or it is adsorbed to clay and humus particles and can become available to the plant at a later stage (Maynard 1989). Ammonium can, however, also be nitrified to form nitrate and thus increase the chance of nitrogen leaching (Maynard 1989; Taiz and Zeiger 2010). The nitrification of ammonium to nitrate does not pose a huge problem with regard to nitrogen entering the soil from organic matter, as it is released very slowly and thus reduces the risk of nitrification and leaching taking place (Maynard 1989). A possible explanation therefore for the higher nitrate levels in the soil water from the control treatment in the heavier soil site is that the physical, chemical and biological properties of the soil in the control treatment allowed for more nitrification to occur as well as increased leaching. Considerably higher nitrate levels were found in the soil water from the lighter soil site compared to that of the heavy loam site. This can be attributed to the lighter textured soil allowing for more drainage and thus leaching of nitrate, confirming previous research (Stirzaker 2003).

Root Study

Overall increases in root numbers were found over all of the treatments and in both sites, from 2010 to 2012. However, the compost and woodchips treatments in the heavier soil site, and all of the geotextile fabric and woodchips treatment in the lighter soil site ultimately resulted in the greatest increases, greatest distribution and highest numbers of fine and intermediate roots in 2012. This is imperative for optimal acquisition of nutrients and water. The increased distribution thereof corresponds with a study by Lang et al. (2001) where it was observed that root length density was greater, and extended deeper in the profile under mulched surfaces (black plastic and sawdust mulches) as appose too un-mulched surfaces. They attributed this to a more favourable soil environment created by mulching the soil surface.

The favourable soil environment that Lang et al. (2001) refer to as a result of mulching, can include various aspects of the soil. On closer inspection, physical, chemical and biological aspects need to be addressed in order to attribute a favourable soil environment to mulching.

In the heavier soil site, the compost treatment, amongst others, excelled in root growth and development. Referring to the physical analysis of this treatment, improved physical properties such as lower resistances (1942.5 ohm – 28.27.5 ohm) and intermediate bulk densities (1.18 kg ℓ^{-1} – 1.22 kg ℓ^{-1}) compared to the other treatments were achieved in this site (data in Paper 1). The compost treatment was also efficient in keeping the temperatures fairly constant (fluctuations of approximately 2°C - 3°C) during the growing season in both sites and this was accompanied by lower soil water levels (reaching water levels of 30%), compared to the other treatments (data in Paper 1). With proof of over irrigation (Fig. 7), as well as the heavier texture and thus higher water holding capacity of the soil, lower soil water levels are likely to allow for increased root growth due to better aeration (Stolzy 1974; Taiz and Zeiger 2010). Stolzy (1974) and Taiz and Zeiger (2010) reported that factors that contribute to poorly aerated soils have unfavourable effects on root size and depth as oxygen availability is limited to the growing and dividing cells thereof. Reduced mineral uptake by the roots is another response of poor aeration in the soil (Stolzy 1974). In a study by St. Laurent et al. (2008), organic matter in the soil was the highest under mulched treatments and grass lanes, resulting in soil aeration also being highest in these plots. This therefore supports our theory of increased root growth in the organic mulch treatments (compost and woodchips treatments) as a result of better aeration. With these results achieved by the compost mulch treatment, the soil environment was improved with regard to soil physical properties, even though the compost was not physically incorporated in the soil, but accumulated in the soil over time. With regards to the chemical properties, the compost and woodchips treatments frequently followed the superior nutrient levels achieved by the vermi-castings treatment (which largely originated from the vermi-castings mulching material) due to an addition of organic matter which is supported by the remarks of Haynes (1980) and Wolstenholme et al. (1996) (data in Paper 2). The organic mulch treatments also resulted in higher CEC values, ranging between 12.74 cmol(+) kg^{-1} and 10.67 cmol(+) kg^{-1}. These findings are in agreement with those of Lang et al. (2001) who investigated the use of mulching to increase apple fruit storage. They concluded that the CEC was higher in mulched soils, and thus improves the soil environment. In addition, the compost treatment also realised higher mycorrhizeal colonization (reaching levels of 90.2% colonization in 2012) during the three analysed seasons, compared to the other treatments (ranging between 60% and 85% colonization in 2012). Derkowska et al. (2008) emphasised that mycorrhizal colonisation is increased with greater root surface area and the growth of fine feeder roots, and thus explains the higher colonization as a result of the increased fine feeder root growth in this treatment (800 roots <2 mm). All of the above mentioned accreditations of the compost mulch therefore confirm the attributes by Lang et al. (2001), of mulches improving the soil environment.

This scenario was not repeated in the compost treatment in the lighter soil site. The differences in performance by the compost treatment between sites was unexpected, however, is confirmation that mulches function differently on different soil types, especially with access irrigation. As a result, root growth and development did not excel to the extent that it did in heavier soil site.

Contrary to the compost and geotextile fabric treatments, the woodchips treatment excelled in root growth and development in both the heavier soil and lighter soil sites. However, it resulted in unfavourably high resistances (2782.5 ohm – 3375 ohm) in the heavier soil site, but achieved a low bulk density (1.172 kg ℓ^{-1} – 1.37 kg ℓ^{-1}). It therefore resulted in mixed reviews with regards to physical changes to the soil (data in Paper 1). Nevertheless, the woodchips treatment was successful in stabilizing temperature fluctuations (fluctuations of approximately 3°C - 4°C in both sites) and warming the soil (ranging between 20°C and 22°C in the heavier soil site; 20°C and 25°C in the lighter soil site) throughout the season. In the heavier soil site, the treatment resulted in intermediate soil water levels (ranging between 25% and 35%). However, in the lighter soil site, low soil water levels were achieved (ranging between 10% and 25%). A favourable root environment was therefore created by the low bulk density and higher, more stable temperatures. With regard to the compost treatment, the lower soil water levels were likely to favour root growth due to the higher aeration in the soil, confirming reports by Stolzy (1974) and Taiz and Zeiger (2010). In addition, regarding chemical properties, the compost and woodchips treatments frequently followed the superior nutrient levels achieved by the vermi-castings treatment, which is attributed to an addition of organic matter (Haynes 1980; Wolstenholme et al. 1996) (data in Paper 2). The soil biota was not drastically influenced by the woodchips treatment, other than an increase in plant parasitic nematodes (7% in increase from 2010 to 2012) and the highest percentage in 2012 (52%) in the heavier soil site, which may be attributed to the high root count in these treatments and needs to be confirmed (Storey and Hugo 2010). In the same site, the treatment also resulted in a significantly higher free-living nematode population in the 15 – 30 cm soil layer (588 free-living nematode; 87%). This may be attributed to the potential increase in organic matter in the soil accompanied with the use of organic mulches, resulting in more food being made available to free-living nematodes, and thus encouraging their populations to increase (Storey and Hugo 2010). In this study, accreditations of the woodchips mulch therefore confirm the attributes by Lang et al. (2001), regarding mulches and the improvement of the soil environment.

In the lighter soil site, the geotextile fabric treatment excelled in root growth and development. Temperatures did not fluctuate as much in the lighter soil site (fluctuations of approximately 6°C), as they did in the heavier soil site (fluctuations of approximately 9°C). Soil water levels were also lower in the lighter soil site (ranging between 20% and 30%), compared to the heavier soil site (ranging between 40% and 50%), which suggests that more drainage occurred, favouring root growth in over irrigated conditions. This may explain the better performance of the geotextile fabric with regard to root growth in the lighter soil site, compared to the heavier soil site. The intermediate bulk density, higher temperatures and lower soil water levels achieved by this treatment in the lighter soil site, contributed to the improvement of soil environment which Lang et al. (2001) refer to. This is confirmed by reports by Pregitzer et al. (2000) that root growth increases with increasing soil temperatures up to a point, at which the root's optimum growth temperature is reached. Although temperatures fluctuated somewhat in the geotextile fabric treatment, they did not always vary as much as the control treatment did, and it also retained more soil water than the control treatment, providing it with buffering effects on the roots.

The chemical properties of the soil were not improved as much by the geotextile fabric treatment as the organic mulch treatments, again confirming comments with regard to organic mulches increasing organic matter in the soil and thus nutritional status (Haynes 1980; Wolstenholme et al. 1996). The geotextile fabric treatment did not feature prominently with regard to the soil biota (data in Paper 3). Therefore, in this case, better root growth (743 root <2 mm) was primarily supported by the more stable temperatures and lower soil water levels achieved by the geotextile fabric treatment in the lighter soil site.

The vermi-castings treatment did not excel in root growth and development to the same extent as the other organic mulches. The physical, chemical and biological aspect of the soil environment could not explain the lack of response of this treatment in either site (data in

Paper 1, 2 and 3). On the contrary, it improved the overall soil environment (data in Paper 1, 2 and 3). The vermi-castings treatment was very effective in improving physical characteristics of the heavier soil site as it achieved the lowest resistance (1465 ohm – 2345 ohm) and intermediate bulk densities (1.2 kg ℓ^{-1}). Due to the improved physical characteristics of the soil, soil water and temperature levels were stabilized and remained intermediate compared to the other treatments in both sites (data in Paper 1). The vermi-castings treatment was as effective in preventing temperature fluctuations as the woodchips treatment was (fluctuations of approximately 3°C - 4°C in both sites) and water contents in the lighter soil site occurred at intermediate to high levels (ranging between 20% and 30%). The primary attributes to mulching (temperature stabilization and water conservation) were therefore achieved by the vermi-castings treatment in both sites, supporting work by Baver et al. (1972), Haynes (1980) and Wolstenholme et al. (1996). It was also superior in increasing nutrient levels in the soil of the heavier soil site, compared to the other organic mulch treatments (data in Paper 2). In contrast to the heavier soil site, none of the other treatments ameliorated the nutrient status of the lighter soil site, with the exception of the increased percentage C as a result of the compost and vermi-castings treatments (data in Paper 2). The significantly higher levels of nutrients (macro and micro) (P, N, K, Mg, Zn, Mn, B) and exchangeable cations (Na^+, K^+, Ca^+, Mg^+) achieved by the vermi-castings treatment in the heavier soil site were largely due to the notably higher nutrients in the mulching material at application In addition to directly affecting the nutrient status, the vermi-castings treatment retained higher/intermediate soil water and temperatures which probably allowed these nutrients to become more available to the plant, confirming reports by Giulivo (1990). Root growth and distribution did not increase to the extent that the other mulch (organic and inorganic) treatments did, but was still higher than the control treatment. The root/shoot ratio of trees is significantly influenced by the soil nutrient status, availability and water status (Giulivo 1990). Giulivo (1990) also mentioned that soils with high nutrient and water availability resulted in augmented shoot growth in comparison to root growth. He attributed this to an increase in biomass and assimilation rates of the shoots and a decrease thereof of the fine roots. A profusion of available nutrients in the soil may thus initiate an increase in the rate of shoot growth to the detriment of root growth, resulting in a plant with a relatively small root system (Chapin 1980; Ericsson 1995; Forde and Lorenzo 2001; Taiz and Zeiger 2010). In addition, the higher amount of nitrate leaching out of the root zone that took place in the vermi-castings treatment, may result in decreased vegetative growth and thus less root growth. This may partially explain the lack of root growth as a result of the vermi-castings treatment, compared to the other treatments. This is further supported by findings of Forde and Lorenzo (2001) suggesting that root growth and branching is not only dependent on the external soil nutrient levels, but also the internal nutrient status of the plant, and Drew et al. (1973) that newly branched barley root numbers in the middle section of the root profile were considerably lower if top and bottom sections of the root profile where supplied with 1 mM NO_3^- as opposed to 0.01 mM NO_3^-. The vermi-castings treatment therefore created a superior soil environment favourable to accommodate the roots, and thus enabling the tree to put less energy into root growth as the trees in the other treatments, and more into above ground tree physiology (data in v.d. Merwe 2012, data unpublished). With reference to the fruit mineral analysis (following) nutrient status of fruit from the vermi-castings treatment where higher compared to fruit from other treatments. Atkinson (1983) found that water and nutrient uptake is not limited to white active roots, although they are responsible for the majority thereof. Older roots can also access these resources and uptake is not necessarily limited to root age (Wilson 1974; Atkinson and Wilson 1980). Thus new, white active roots might therefore not have been a prerequisite for efficient uptake of these resources by the trees in the vermi-castings treatment to the same extent of trees in the other mulch treatments. The lower mycorrhizal colonization in the vermi-castings treatment also confirmed this explanation, as mycorrhizea are suppressed by the plant if sufficient nutrients are available.

Weed Study

Weed counts in the heavier soil site were approximately 40% higher in the lighter soil site than the heavier soil site. These findings are attributed to the higher water content in the heavier soil site compared to that of the lighter soil site, which favours growth of *Cyperus rotundus* (Reinhart et al. 2000). They also stated that *Cyperus rotundus* do not germinate unless soil water conditions are above 13% to 16%. Soil water levels in the heavier soil site generally ranged between 40% and 50%, and in the lighter soil site between 15% and 30%, which suited the germination of *Cyperus rotundus*.

The geotextile fabric treatment was the superior treatment with regard to weed control and suppression, as it resulted in considerably low weed counts in both sites. Certain mulching materials, particularly black inorganic materials, have proved to be beneficial in reducing weed populations and thus herbicide applications, as the black plastic limits light on and near the soil surface, preventing germination (Cross et al. 1993; Fourie et al. 2011). In spite of no improvement of the soil environment conditions, there was still an increase in root growth and development in the geotextile fabric. This could have been partly due to lack of weed competition, confirming results by Cross et al. (1993) and Fourie et al. (2011). Increased root growth in the other treatments was usually substantiated by improved soil environments compared to the geotextile fabric treatment that allowed root growth, in spite of weed competition. Soil water levels in the geotextile fabric treatment were also frequently found to be higher than the other mulch treatments, allowing for less competition for water between roots and weeds in the geotextile fabric treatment.

Fruit Yield and Quality

The overall decrease in yield efficiency observed in both sites from 2009 to 2012, was also a trend of other 'Cripps' Pink' orchards (personal communication with Fanie Myburgh and Ben de Villiers, farm management) and thus not a direct effect of the treatments.

In the heavier soil site, the vermi-castings and woodchips treatments consistently realised higher to intermediate yield efficiencies over the four years. This is supported by studies by Neilsen et al. (2004), where yield efficiency was found to increase under mulching practices. As yield efficiency is directly related to soil water, a possible explanation for the higher to intermediate yield efficiencies achieved by the vermi-castings and woodchips treatments is that soil water levels in these treatments remained consistently higher to intermediate compared to the other treatments (data in Paper 1). The higher yield efficiency achieved by the woodchips treatment is credit to an improved root system as a result of this treatment (discussed above). The improved root system is capable of supporting greater yield efficiencies due to optimal use of soil water (Neilsen et al. 2004). With regard to the higher yield efficiency achieved by the vermi-castings treatment, root improvements where not to the extent of the other treatments, as determined earlier, however, a superior soil environment was achieved and thus an increased root count was not required for the tree to fulfil its requirements to produce a greater yield efficiency. In addition, the higher amount of nitrate leaching out of the root zone that took place in the vermi-castings treatment, may result in decreased vegetative growth and thus less root growth. More energy was available for reproductive growth in this regard. The compost treatment, however, resulted in consistently lower yield efficiencies which are supported by studies by Hartley and Rahman (1998) where compost mulching was used. With reference to nitrate leaching, less nitrate was leached from the compost treatment compared to the control and vermi-castings treatments, and thus more vegetative growth may have occurred as opposed to reproductive growth. This statement is also supported by the higher root counts, and thus increased vegetative growth, in the heavier soil site in the compost treatment compared to the other treatments, discussed earlier.

Schrader et al. (2003) reported that associated water stress has proved to aggravate the incidence of sunburn in fruit, as tree performance is impacted as a result and is directly related to the incidence and severity of sunburn. Although the trees were not under water stress (data in Paper 1) too much water can also be regarded as stress due to the lack of oxygen in the soil (Wooldridge 1994). The trees therefore seize to take up water effectively which may result in pooper tree performance and thus increased incidence of sunburn. However, Wooldridge (1994) brings to light that conditions do not need to be saturated in order to result in poor aeration in the soil and thus poor tree performance. He attributes this to restricted gaseous exchange between the soil and the above surface atmosphere. With the addition of a mulch layer on top of the soil surface, although not quantified, gaseous exchange between the overlying atmosphere and the soil may be limited with the use of certain mulches. We can therefore speculate that this may have been the case with the compost treatment as sunburn was particularly dire as a result of this treatment. The lower soil water levels achieved by this treatment (data in Paper 1) may have resulted in higher root counts, however, also resulted in less dissolved oxygen in the water that roots rely on during times of poor aeration (Wooldridge 1994). A poorer performance by the tree in this treatment was the ultimate outcome. This is further supported by the higher to intermediate soil water levels found in the geotextile fabric and vermi-castings treatments, and the increased root count and superior soil environment respectively, and the corresponding lower incidences of sunburn as a result of these treatments.

With regards to fruit quality, as well as the effects of fruit minerals, no consistent improvements occurred for any treatments, for either site. With the consideration of the higher soil nutrients as result of mulching (data in Paper 2), particularly that of the vermi-castings treatment, fruit quality benefits may occur as a result in years to come. Although no significant differences where found between treatments with regard to the fruit mineral analysis, the vermi-castings treatment consistently resulted in higher levels of N, P and K, all of which are important for superior fruit quality (Kotze 2001).

Conclusion

In general, an increase in root number and greater distribution thereof in both sites across treatments was noted from 2010 to 2012 and is likely an effect of improved irrigation management.

It is clear, from the adjustments in irrigation in 2011, that with slightly lower water deliverance, greater root volumes occurred. The treatments which resulted in consistently lower to intermediate soil water levels, ultimately achieved greater root volumes, however, not necessarily improved tree performance.

The organic mulch treatments, which resulted in higher organic matter in the upper soil layers, particularly that of the woodchips and compost treatments in the heavier soil site, achieved better fine root counts, and better distribution thereof. However, the inorganic treatment ultimately performed the best in this regard in the lighter soil site. We can therefore conclude that the soil water status greatly impacts root growth, development and distribution, and that the nature of the soil being covered by a mulch determines the effect thereof. We also found that greater root volume did not necessarily achieve superior tree performance and thus fruit yield and quality. We can therefore conclude that the superior soil and root environment achieved by the vermi-castings treatment did not necessarily increase root numbers to the extent of the other mulch treatments, but created an efficient root system that was able to make good use of the water and nutrients in the soil. As a result, the vermi-castings treatment resulted in the best tree performance, highest yield efficiency and lowest incidence of sunburn. Ultimately, by improving the root environment with a mulch, root growth is not necessarily enhanced, but, root efficiency is enhanced, resulting in superior tree performance.

Although root volumes were altered and improved by mulching, fruit quality, with the exception of sunburn incidence, was not changed. We can therefore conclude that with the beneficial aspects of mulching on the physical, chemical and biological factor of the soil, fruit quality benefits may occur as a result in years to come.

In addition, covering the soil with dark plastic can reduce the germination and growth of weeds considerably, as seen with the geotextile fabric treatment in both the heavier soil and the lighter soil site.

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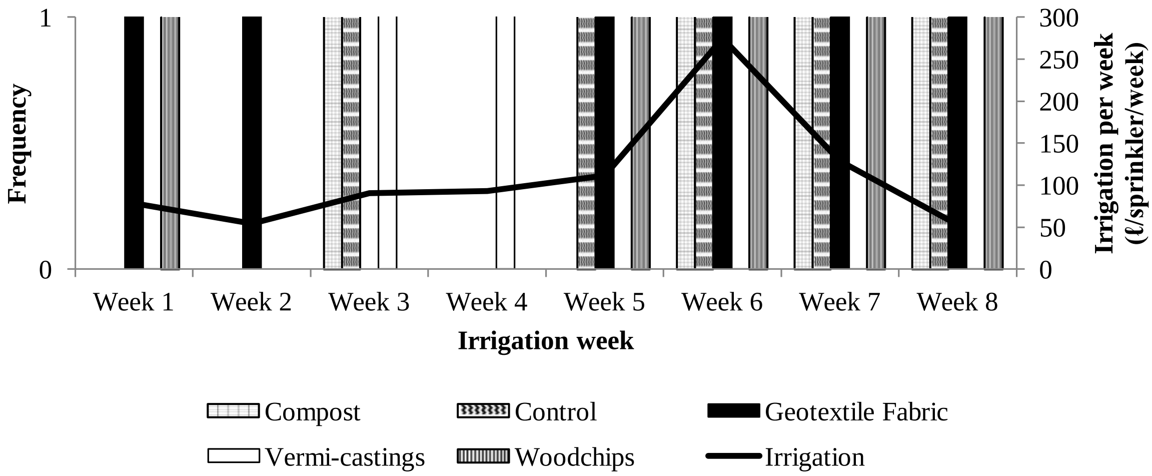

Fig. 1 Depth at which the irrigation wetting front past the 20 cm WFD in the heavier soil site, correlated with the irrigation received per sprinkler per week for a two month period (1 February 2012 – 31 March 2012)

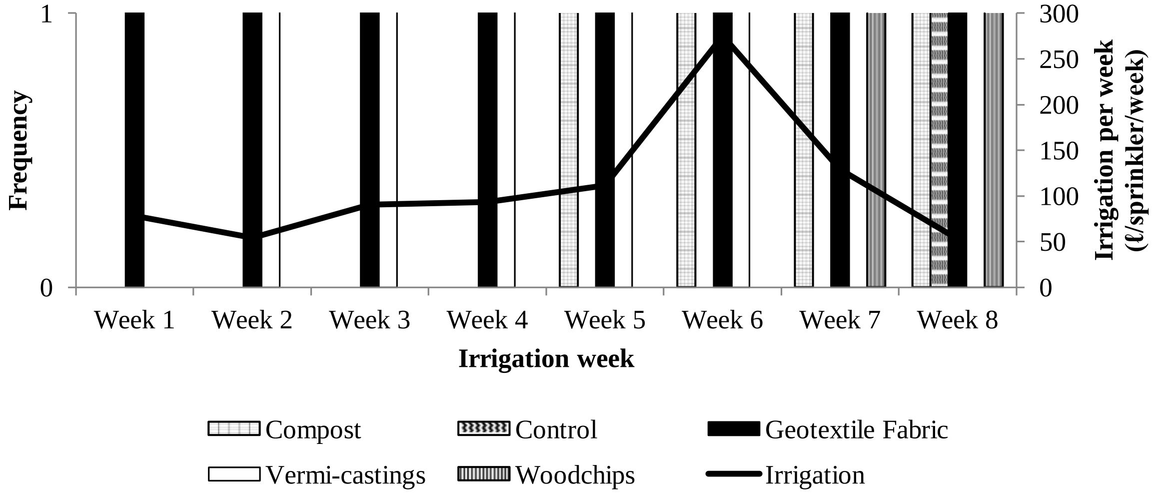

Fig. 2 Depth at which the irrigation wetting front past the 40 cm WFD in the heavier soil site, correlated with the irrigation received per sprinkler per week for a two month period (1 February 2012 – 31 March 2012)

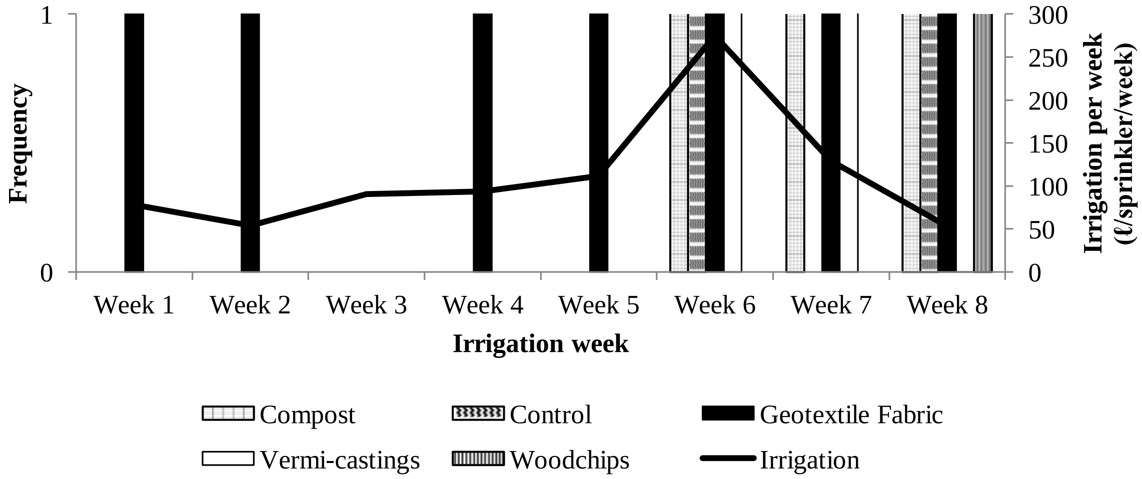

Fig. 3 Depth at which the irrigation wetting front past the 60 cm WFD in the heavier soil site, correlated with the irrigation received per sprinkler per week for a two month period (1 February 2012 – 31 March 2012)

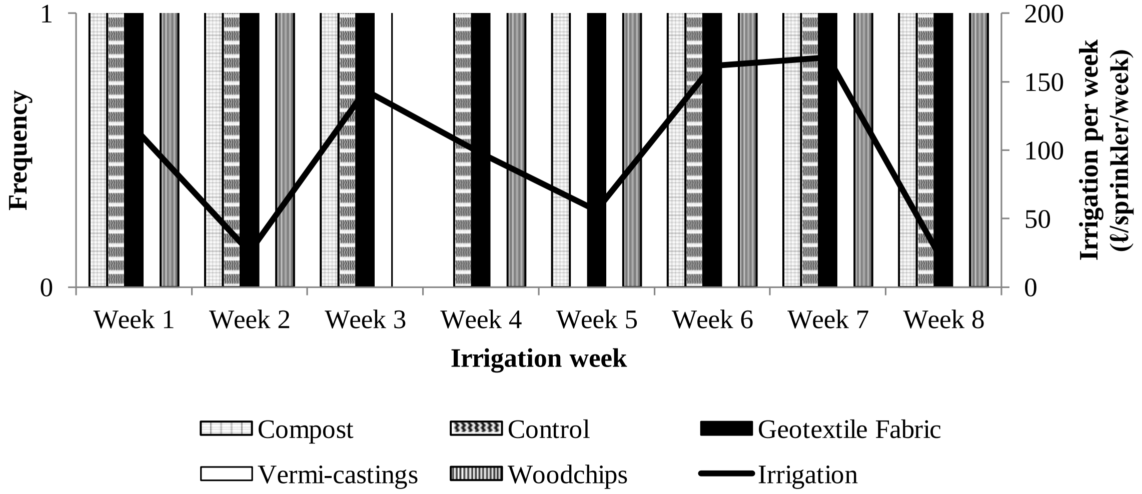

Fig. 4 Depth at which the irrigation wetting front past the 20 cm WFD in the lighter soil site, correlated with the irrigation received per sprinkler per week for a two month period (1 February 2012 – 31 March 2012)

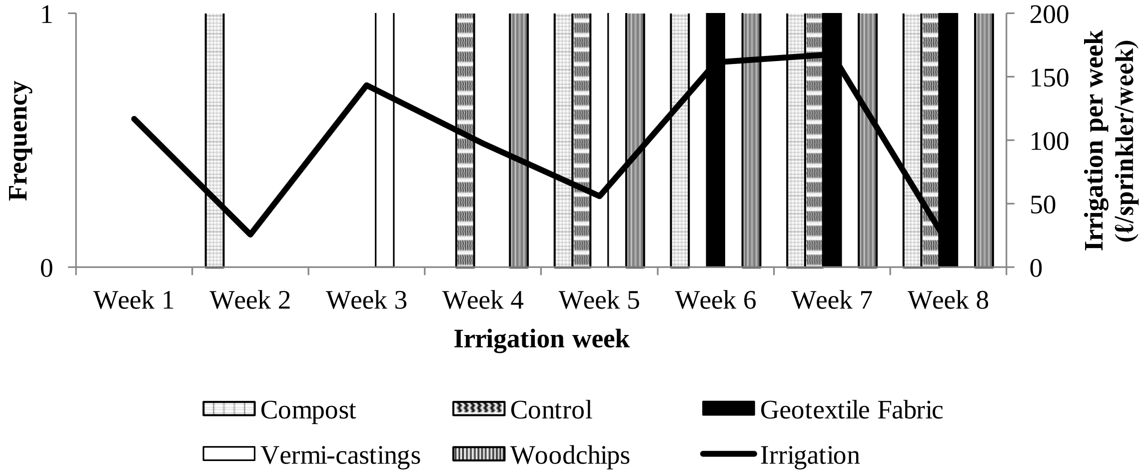

Fig. 5 Depth at which the irrigation wetting front past the 40 cm WFD in the lighter soil site, correlated with the irrigation received per sprinkler per week for a two month period (1 February 2012 – 31 March 2012)

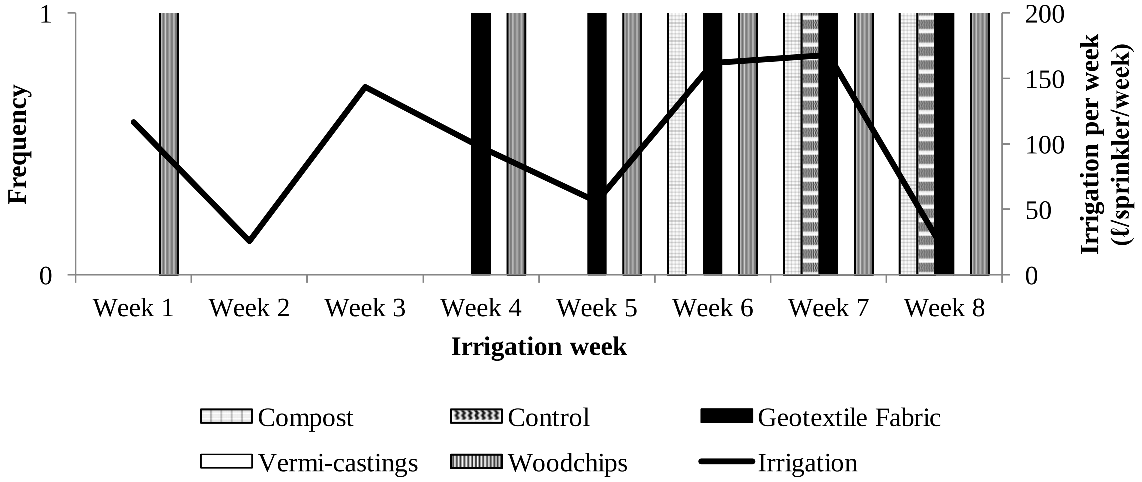

Fig. 6 Depth at which the irrigation wetting front past the 60 cm WFD in the lighter soil site, correlated with the irrigation received per sprinkler per week for a two month period (1 February 2012 – 31 March 2012)

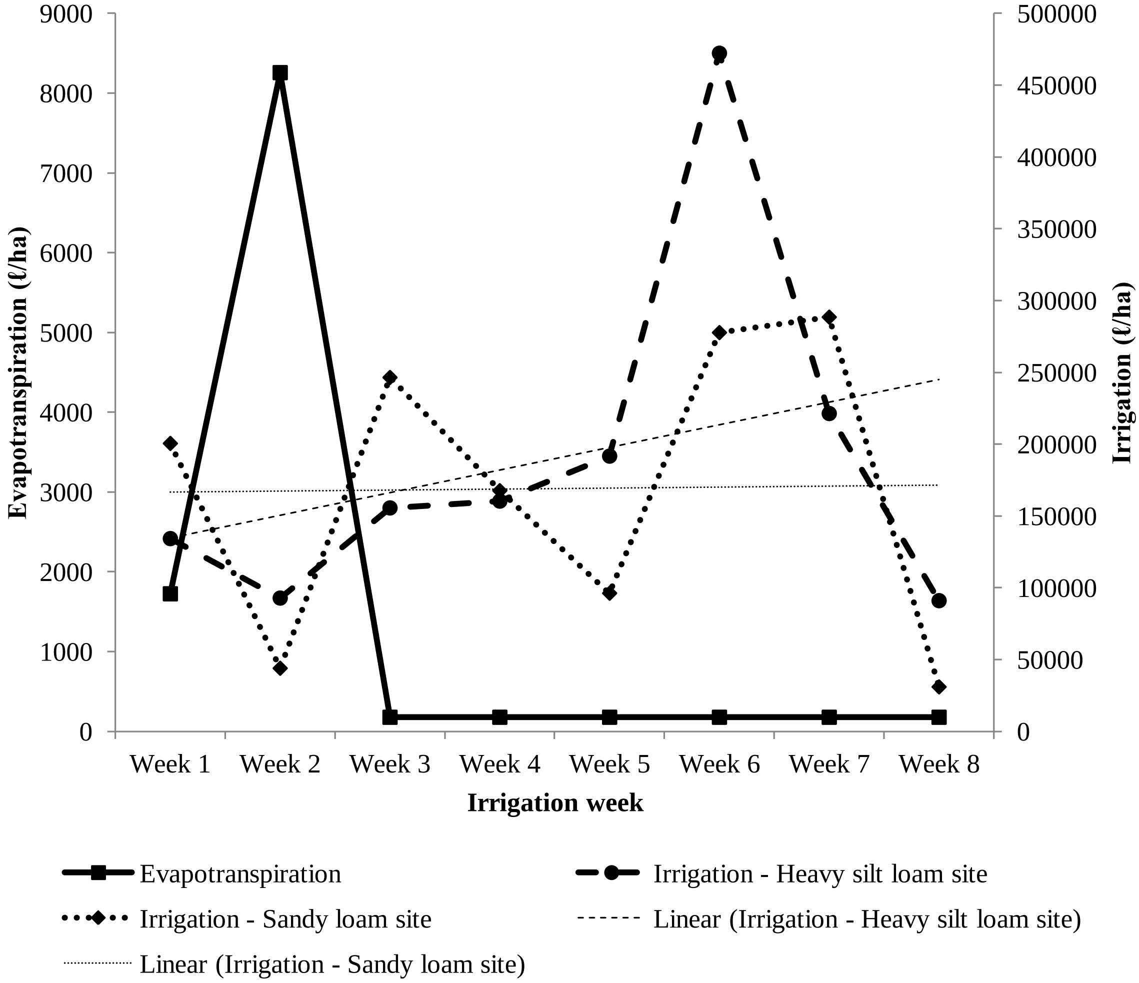

Fig. 7 Irrigation per hector per week in both sites correlated against evapotranspiration per hector per week for a two month period (1 February 2012 – 31 March 2012)

Table 1 Nitrogen fertilizer program as implemented by farm management for 2011/2012

Time of Fertilizer Application	Date	Fertilizer Name	ℓ/ha	Percentage Nitrogen (%)
After Full Bloom	2011/10/25	Orion Plus*	275	8.6
	2011/11/18	Orion Plus*	275	8.6
6 Weeks After Full Bloom	2011/12/28	Triton**	300	16.5
	2011/12/30	Libra***	1200	1.0
After Harvest	2012/05/17	Triton**	350	16.5

* Orion Plus Composition: 8.6% N; 7.3% Ca; 2.3% Mg
**Triton Composition: 16.5% N; 3% Ca; 1% Mg
*** Libra Composition: 1.0% N; 1.0% P; 10% K; 0.4% Mg; 0.5% S

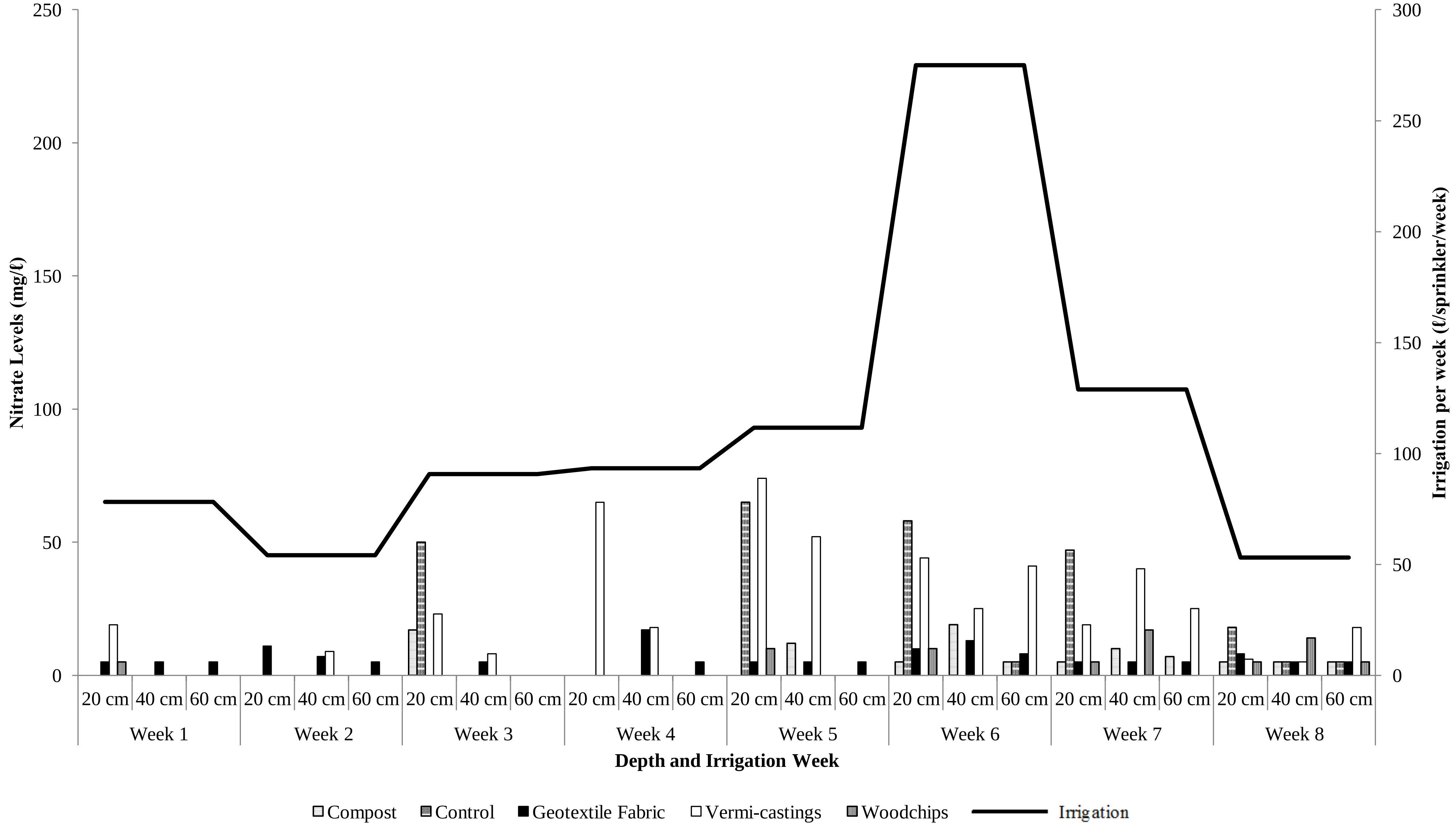

Fig. 8 Nitrate levels in samples of irrigation water caught by the WFDs at 20 cm, 40 cm and 60 cm depths in the heavier soil site, correlated against the irrigation received per sprinkler per week for a two month period (1 February 2012 – 31 March 2012)

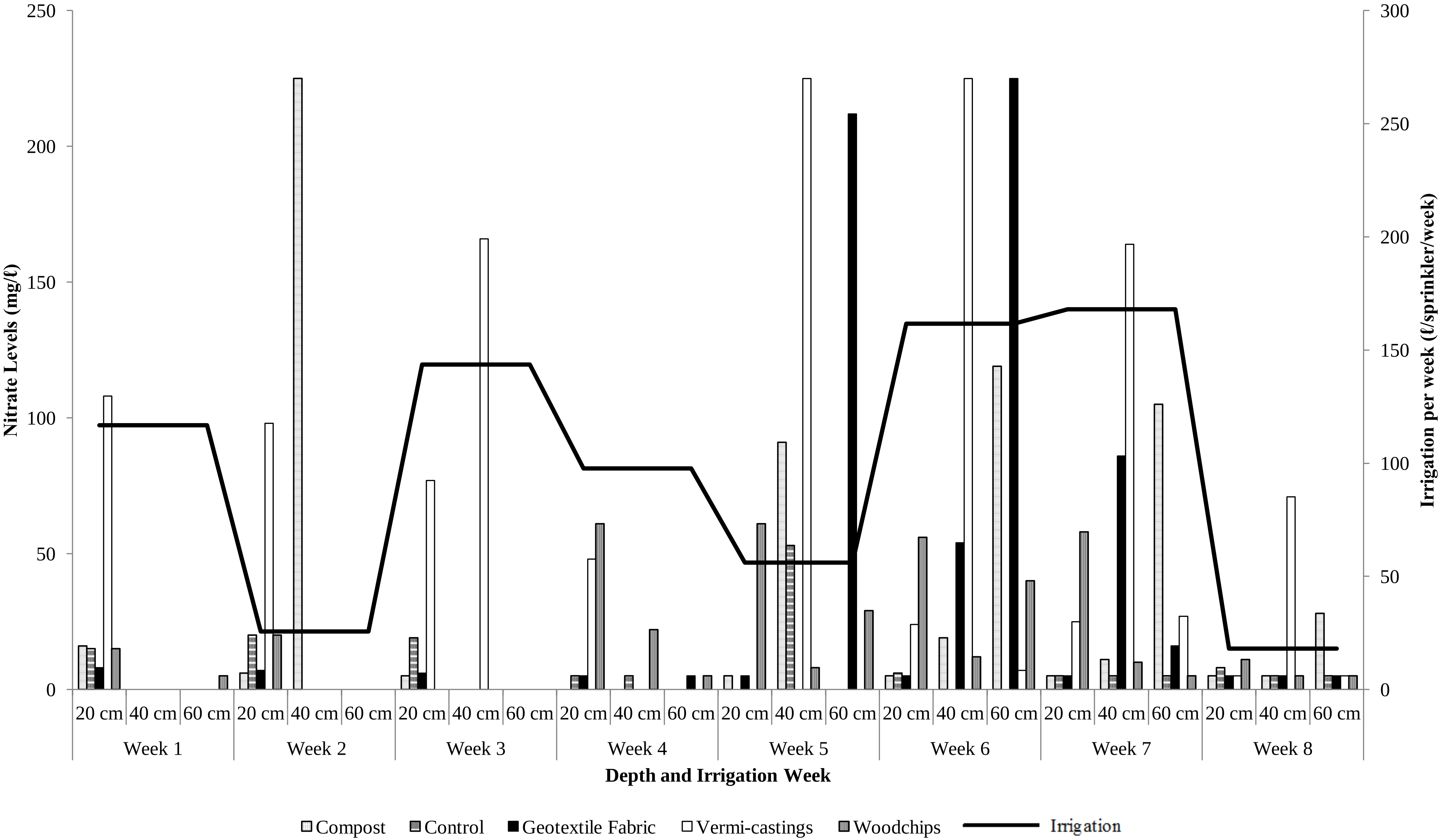

Fig. 9 Nitrate levels in samples of irrigation water caught by the WFDs at 20 cm, 40 cm and 60 cm depths in the lighter soil site, correlated against the irrigation received per sprinkler per week for a two month period (1 February 2012 – 31 March 2012)

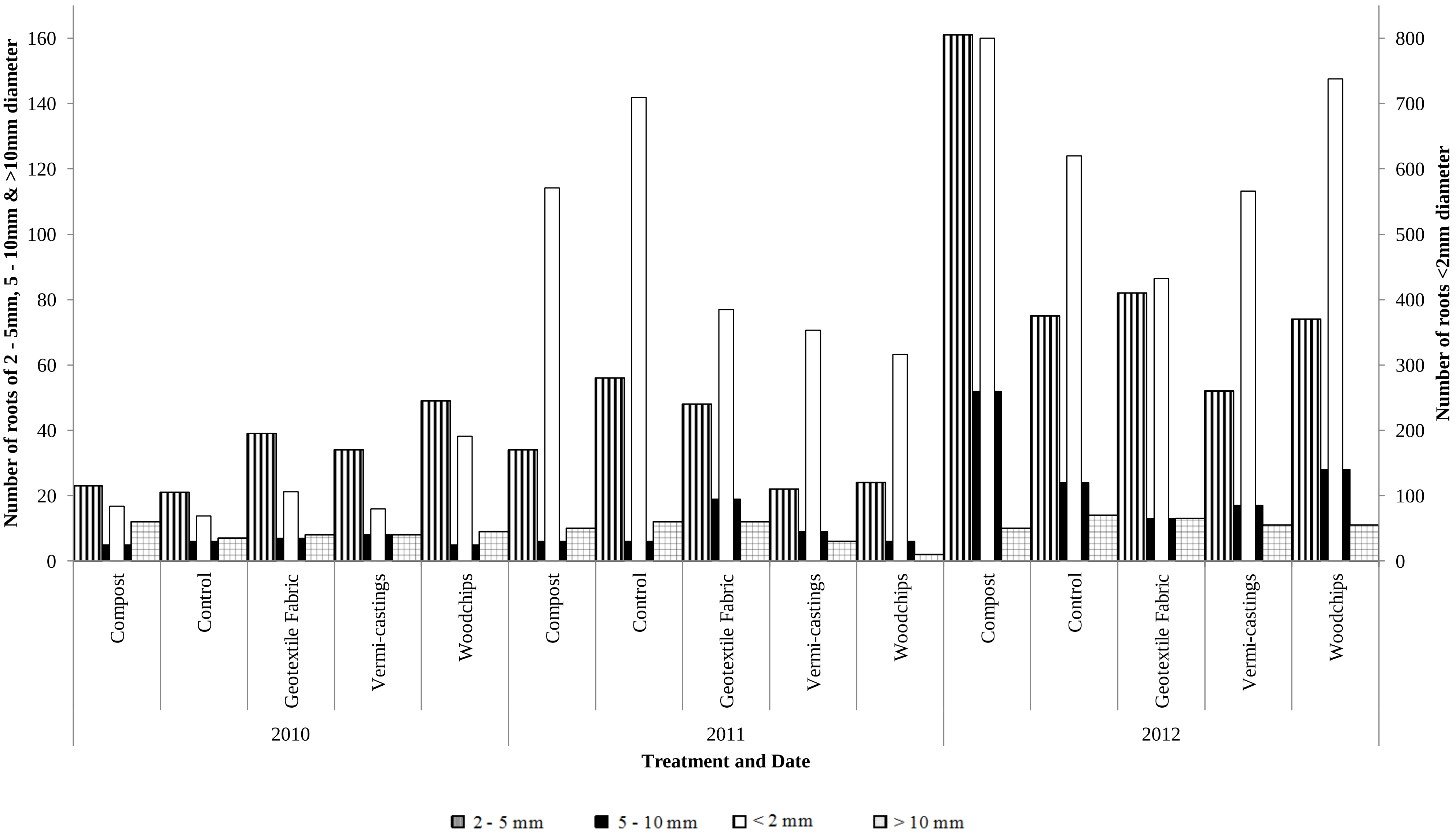

Fig. 10 Total number of roots throughout the profile of one replicate per treatment in the heavier soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter

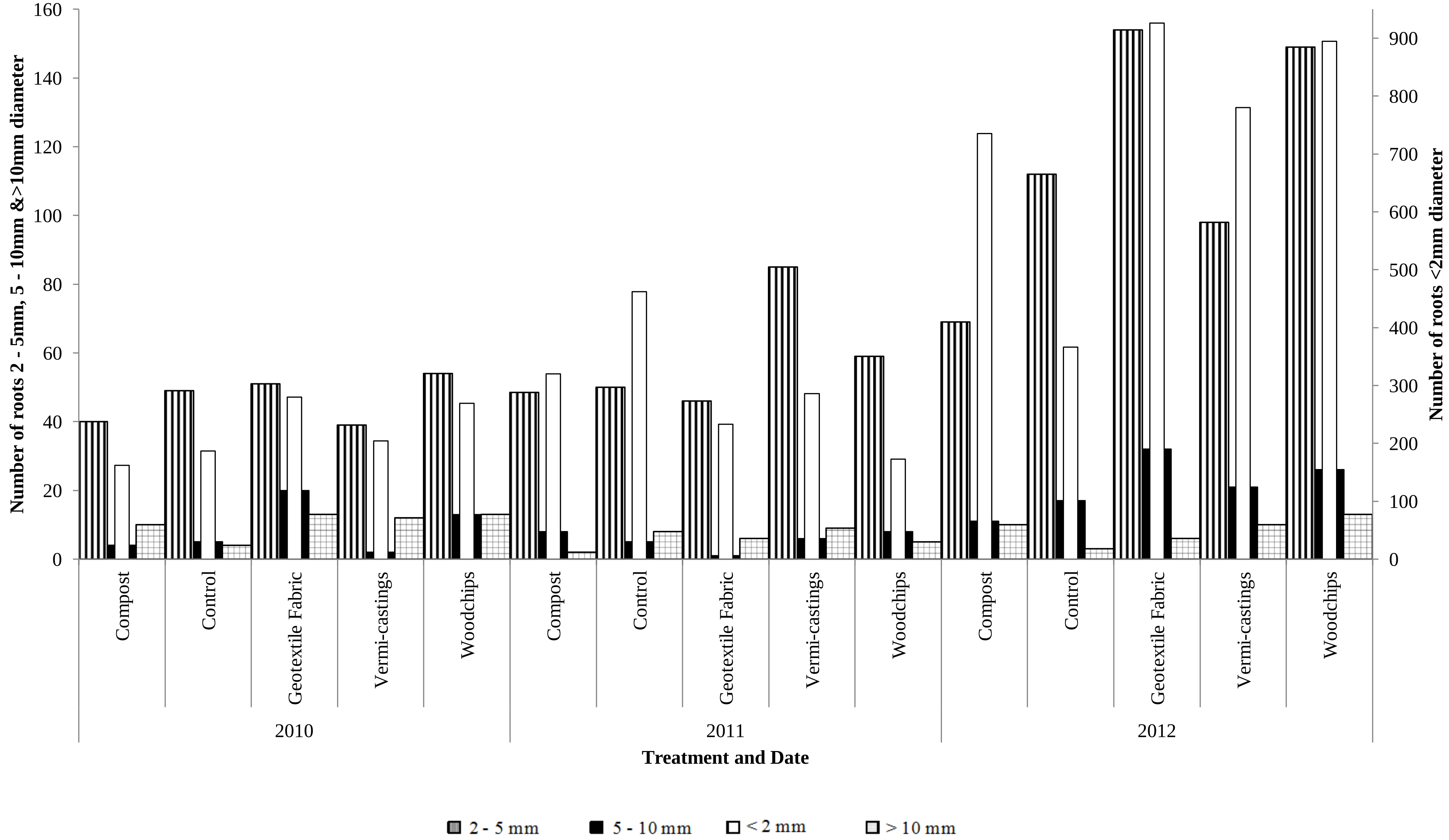

Fig. 11 Total number of roots throughout the profile of one replicate per treatment in the lighter soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter

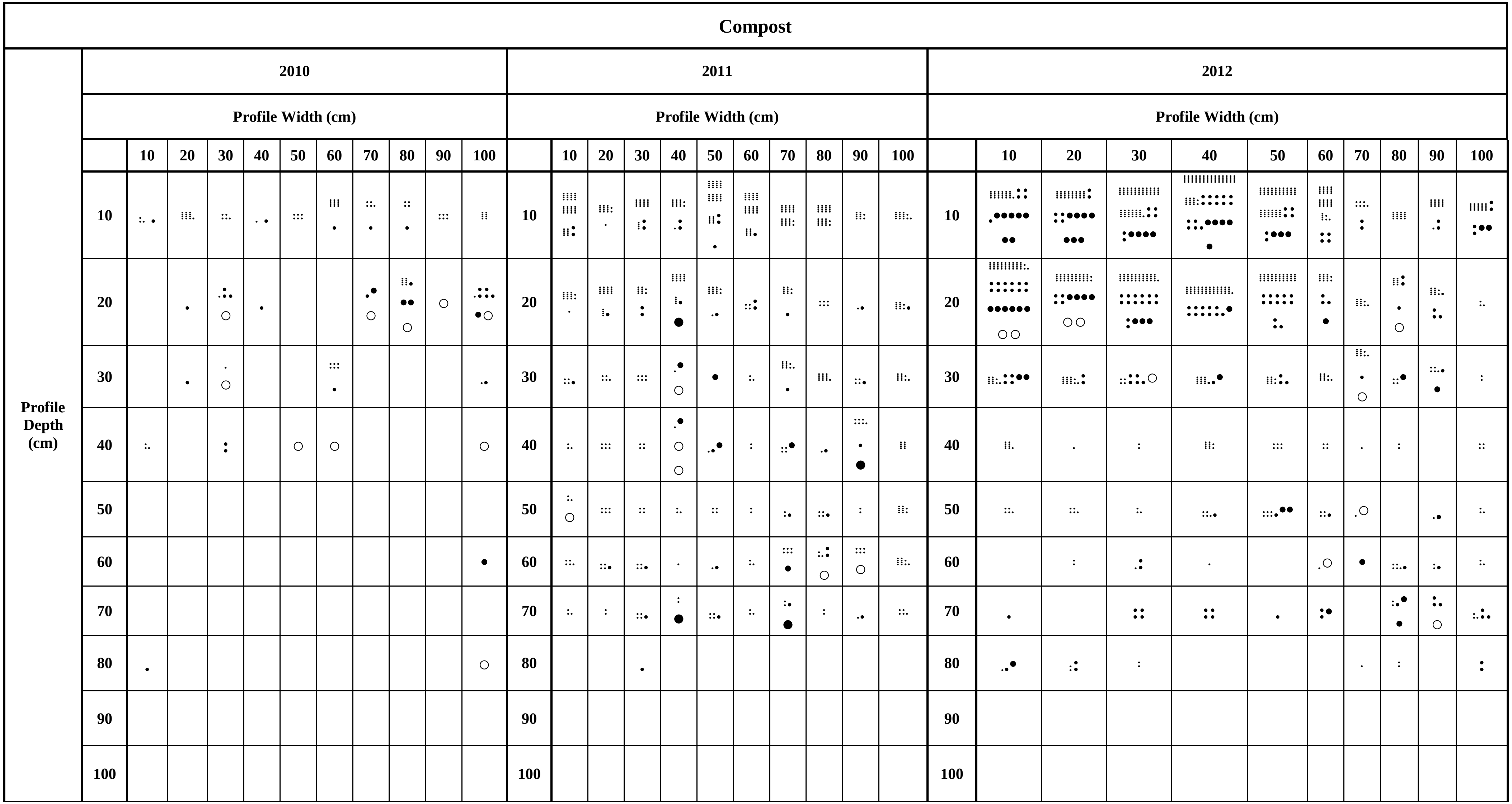

Fig. 12 Total root distribution of the compost treatment at 10 cm intervals down the profile of one replicate per treatment in the heavier soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter* * ⁝ = < 2 mm; **:** = 2-5 mm; • = 5-10 mm; ○ = > 10 mm

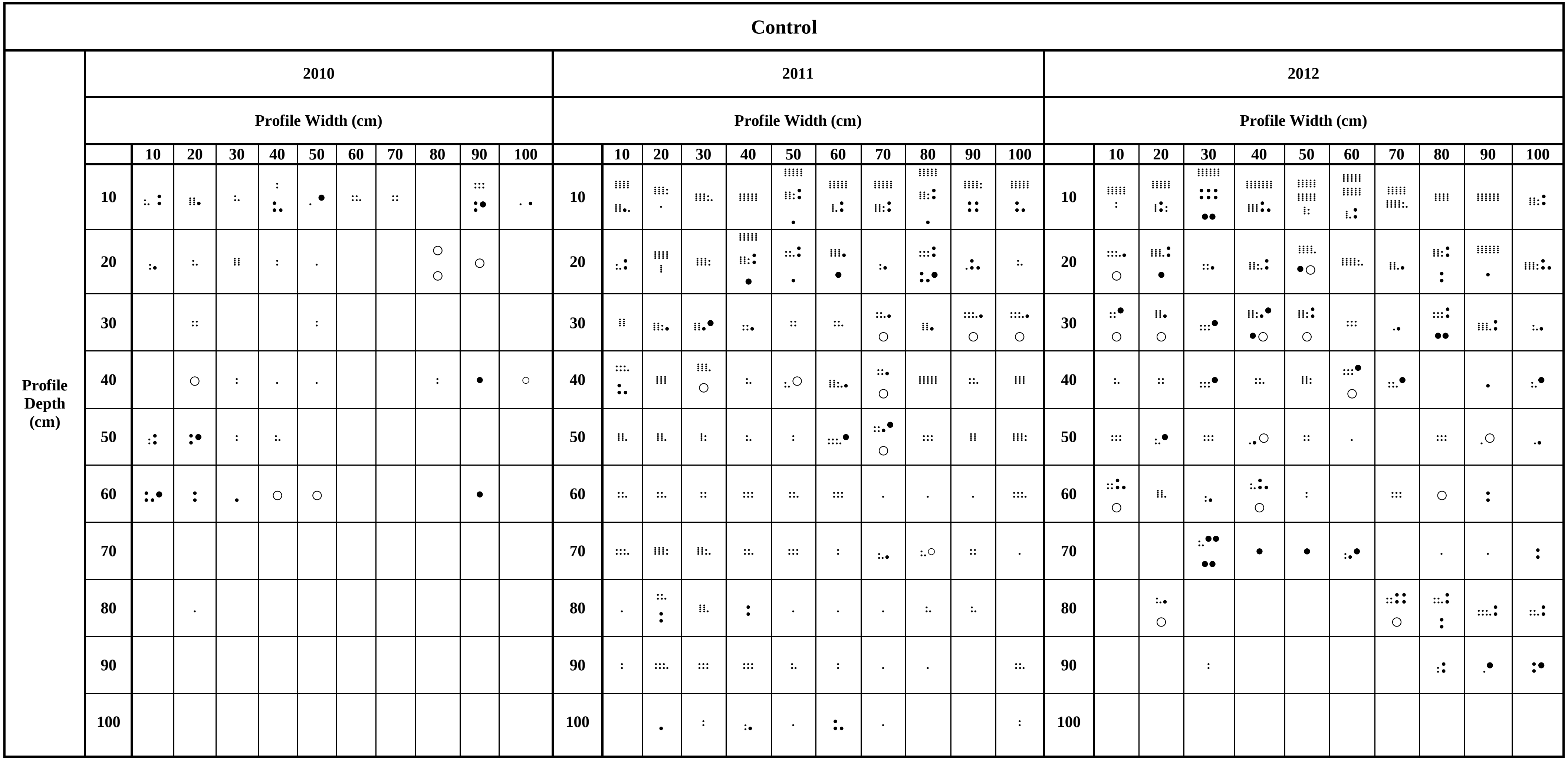

Fig. 13 Total root distribution of the control treatment at 10 cm intervals down the profile of one replicate per treatment in the heavier soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter* * ⁞ = < 2 mm; **:** = 2-5 mm; • = 5-10 mm; ○ = > 10 mm

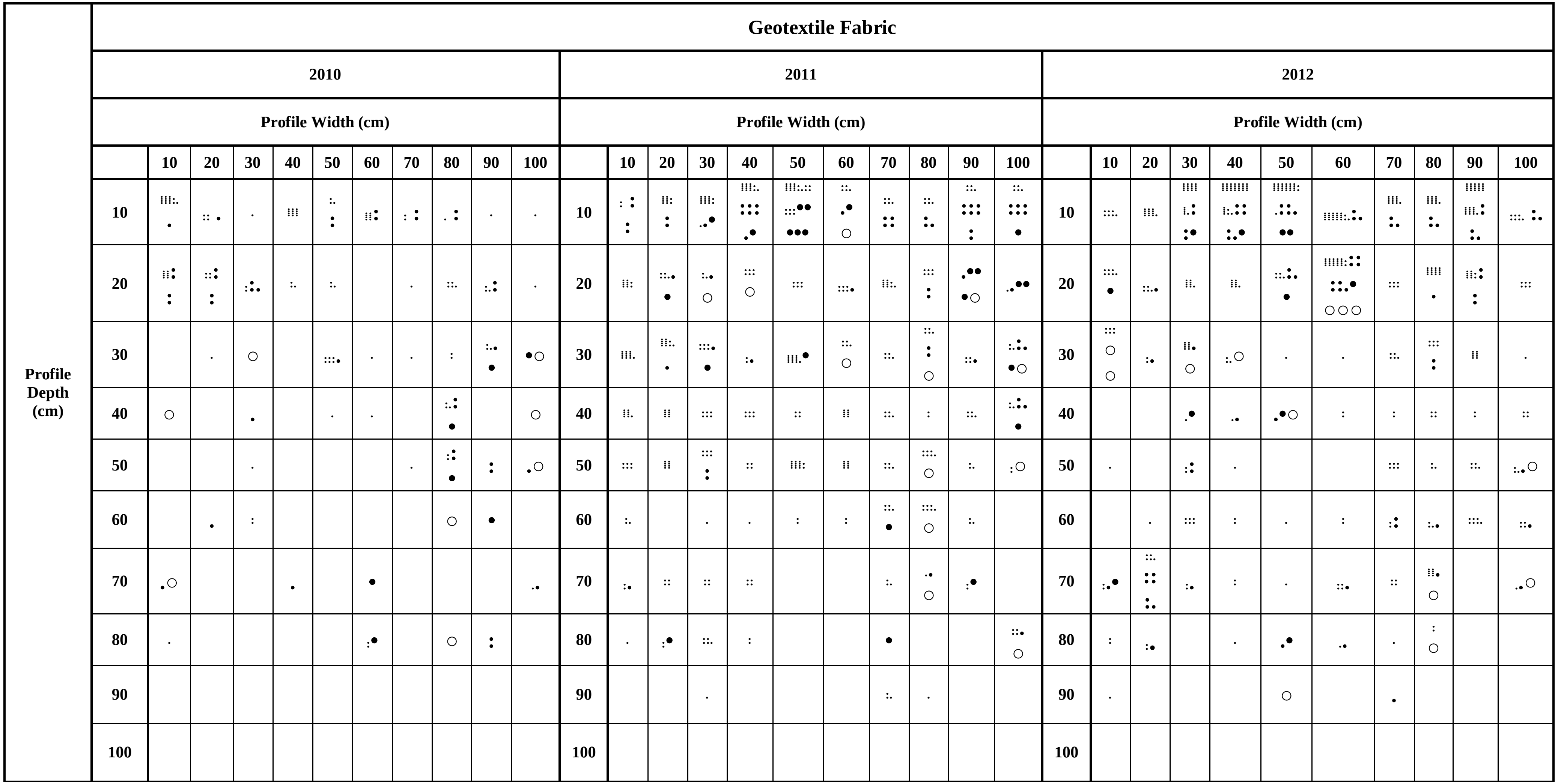

Fig. 14 Total root distribution of the geotextile fabric treatment at 10 cm intervals down the profile of one replicate per treatment in the heavier soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter* * ⁝ = < 2 mm; **:** = 2-5 mm; • = 5-10 mm; ○ = > 10 mm

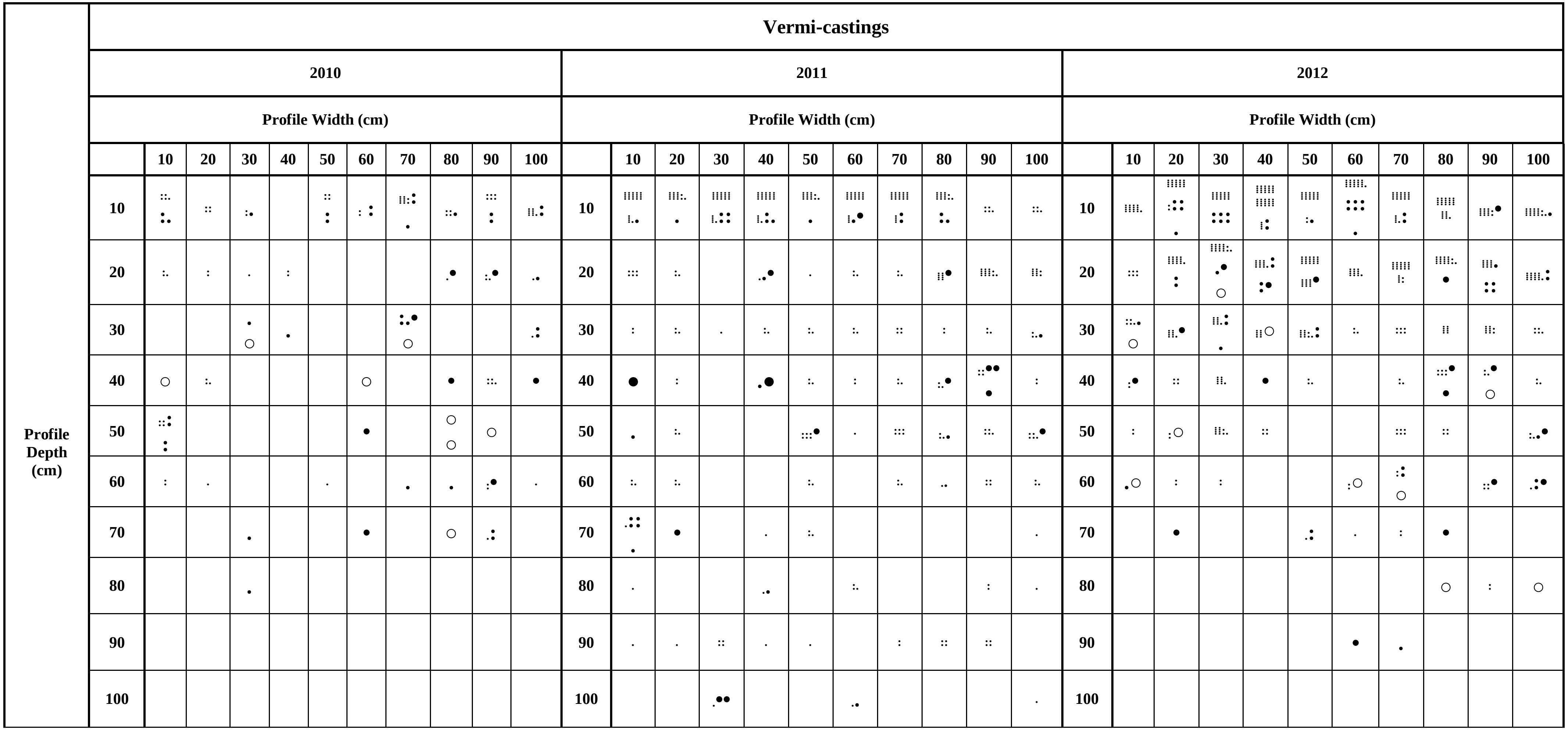

Fig. 15 Total root distribution of the vermi-castings treatment at 10 cm intervals down the profile of one replicate per treatment in the heavier soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter* * ⁝ = < 2 mm; **:** = 2-5 mm; • = 5-10 mm; ○ = > 10 mm

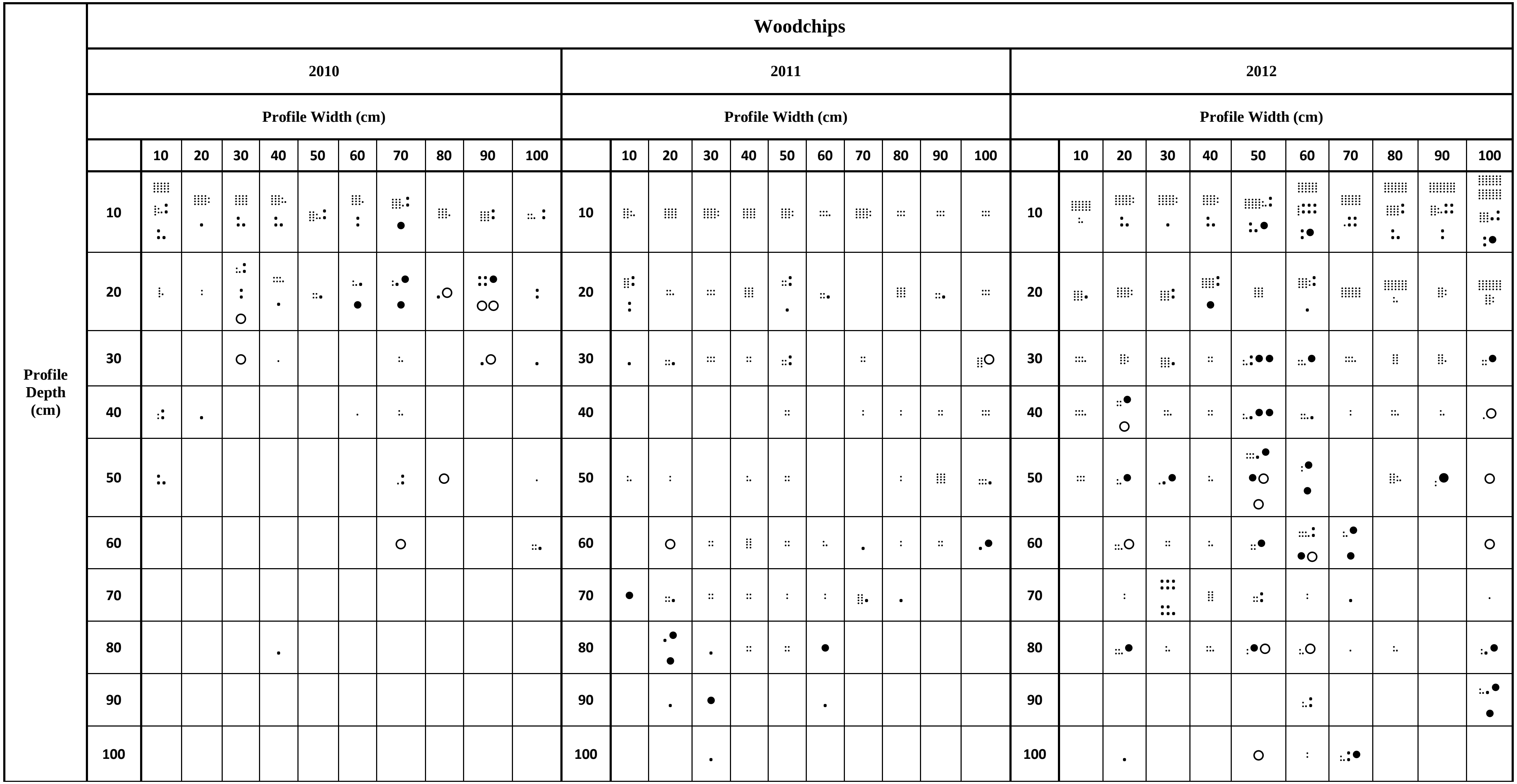

Fig. 16 Total root distribution of the woodchips treatment at 10 cm intervals down the profile of one replicate per treatment in the heavier soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter* * ⁝ = < 2 mm; **:** = 2-5 mm; • = 5-10 mm; ○ = > 10 mm

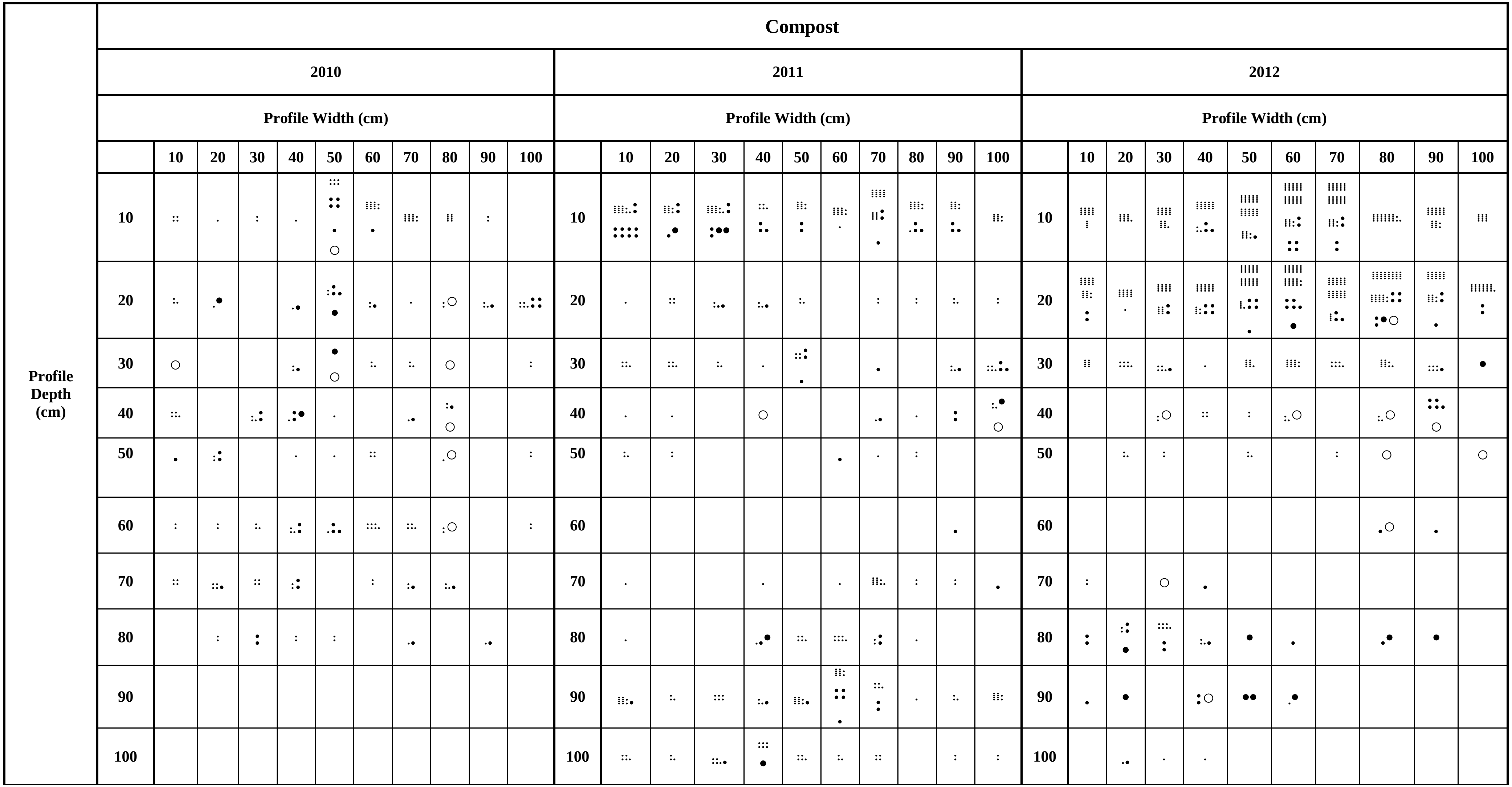

Fig. 17 Total root distribution of the compost treatment at 10 cm intervals down the profile of one replicate per treatment in the lighter soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter* * ⁞ = < 2 mm; **:** = 2-5 mm; ● = 5-10 mm; ○ = > 10 mm

Control

Profile Depth (cm) — **2010** — Profile Width (cm)

Profile Depth (cm)	10	20	30	40	50	60	70	80	90	100
10		·	:. :	⁞⁞:.•	⁞⁞: .:•	⁞⁞:. :	⁞: :: •	::.	:. :•	::. :•
20					:•			:•	.•	
30	•				·	.○			:○ ○	•
40	::	.•						.• ○	:	
50		:.•	:			•		.•	.•	:
60	:		:.:	⁞:: •	⁞: •	:::	:::.	:	·	
70	:.	:::	::	⁞⁞.	::: :	·	·	.•	·	
80			•	::::	:::	·	:	·	::.•	
90										
100										

2011 — Profile Width (cm)

Profile Depth (cm)	10	20	30	40	50	60	70	80	90	100
10	:	::	⁞⁞:	:.	:	⁞⁞	: •	:::.	⁞.	•
20		·		⁞	⁞⁞⁞ ⁞.	::•	:::	:	::	:
30	:•	••		::•	:::					○
40	⁞: :		.○	::	:	:			·	::•
50	⁞: :	:		○	::				•	
60	::•	•	:	:: :	::•	:::	⁞:.	⁞	⁞⁞:	⁞⁞
70	·	::•	:•	⁞⁞:	::	⁞::		⁞⁞: •	⁞⁞•	:::
80		:::	:○ ○○	::•	:::•	⁞:	:.•	:.	::.: •	⁞⁞:
90	:::.	::	⁞⁞:.	:.	::•	⁞⁞	:::	·	:	:.○
100	:•	:::. •	:.○		⁞:.	⁞⁞⁞ :	:::	:.•	⁞	::

2012 — Profile Width (cm)

Profile Depth (cm)	10	20	30	40	50	60	70	80	90	100
10	:::	⁞:	⁞:. •	::. :•	⁞⁞: .:•	⁞⁞.: :	⁞⁞.: •	⁞⁞ :•	⁞⁞⁞⁞. :	⁞⁞⁞⁞⁞⁞ ⁞.
20	·	:::	::. •	:.	⁞⁞:. •	:::.•	⁞:.	⁞: •	⁞⁞:. :	⁞⁞⁞⁞.•
30	::.	:.	:.•			::	::	·	:::.• •	⁞⁞:
40			:•	:				·	·	:
50	○	•			•	•	•			
60	·	:•	•		::	.•	.○	•	•	
70	•	::: •		::	..•		·	:•	:.	:
80	•	:.• •	:•	:•	.::	:•	·	:•	::: •	
90	.•	:	:	:::. •	::.	:::: ::	::.:: •	.:.	.:○	
100	.•	.•	•	.••	.::	:::.•	:.:•	.:		

Fig. 18 Total root distribution of the control treatment at 10 cm intervals down the profile of one replicate per treatment in the lighter soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter* * ⁞ = < 2 mm; : = 2-5 mm; • = 5-10 mm; ○ = > 10 mm

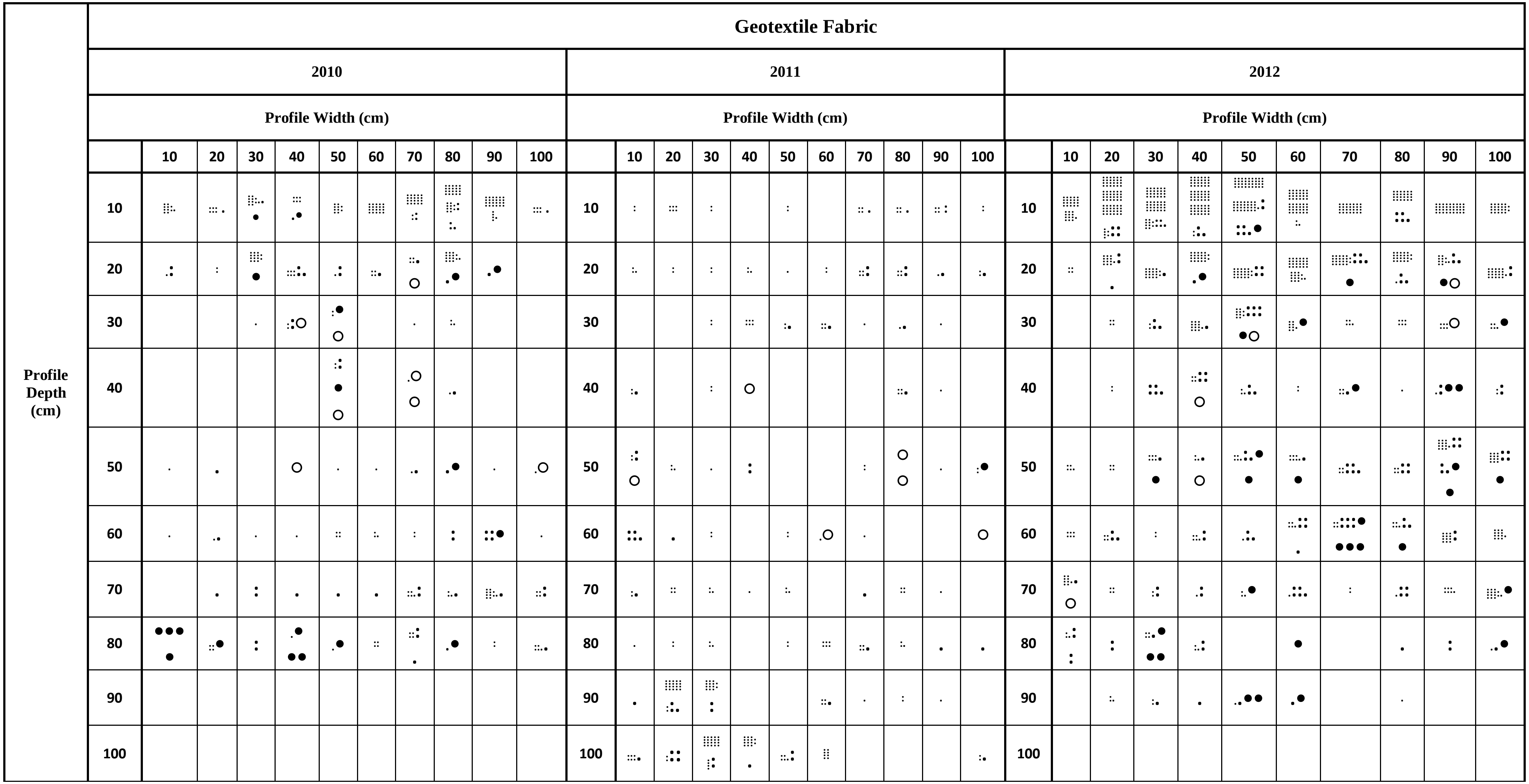

Fig. 19 Total root distribution of the geotextile fabric treatment at 10 cm intervals down the profile of one replicate per treatment in the lighter soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter* * ⁝ = < 2 mm; ⁚ = 2-5 mm; • = 5-10 mm; ○ = > 10 mm

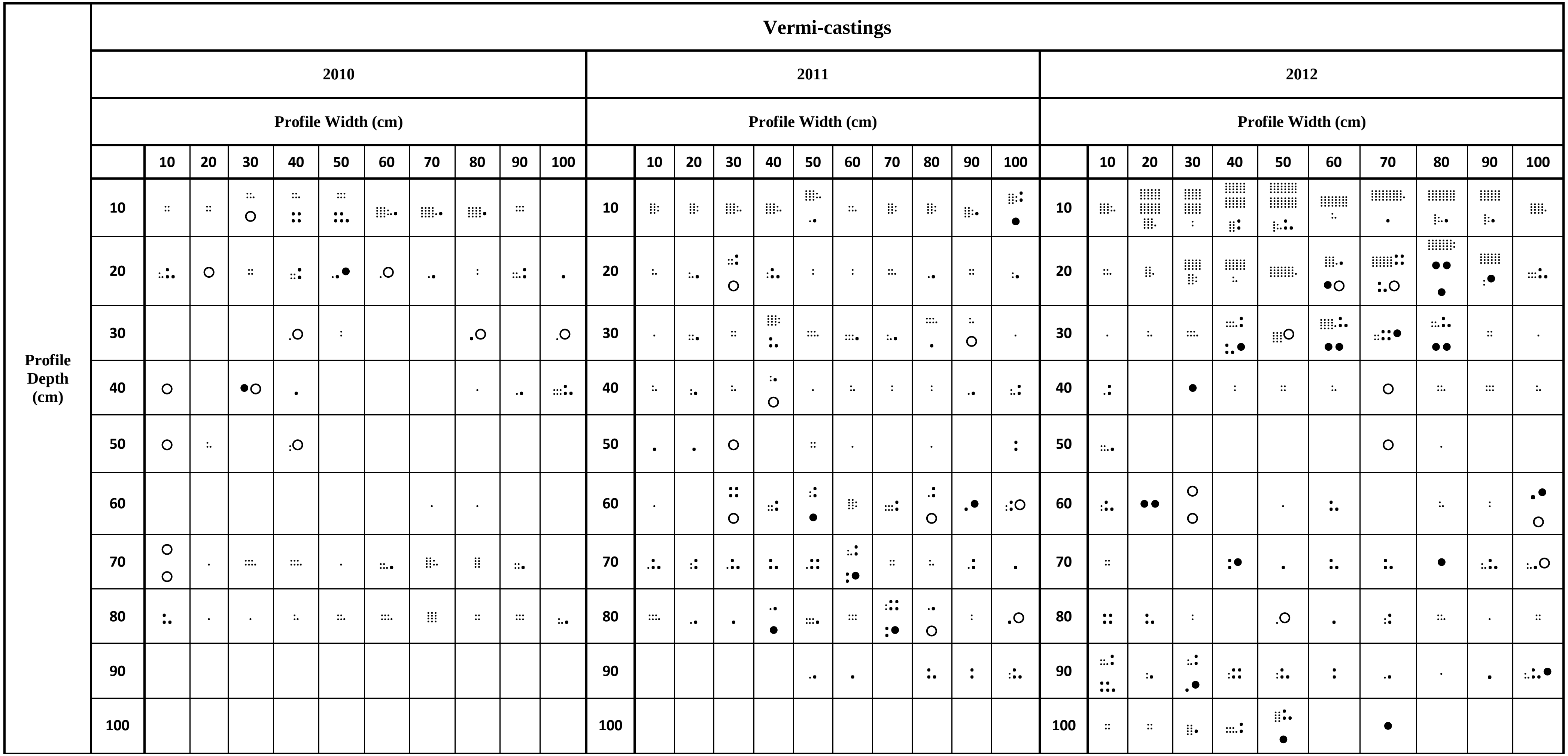

Fig. 20 Total root distribution of the vermi-castings treatment at 10 cm intervals down the profile of one replicate per treatment in the lighter soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter* * ⁝ = < 2 mm; **:** = 2-5 mm; • = 5-10 mm; ○ = > 10 mm

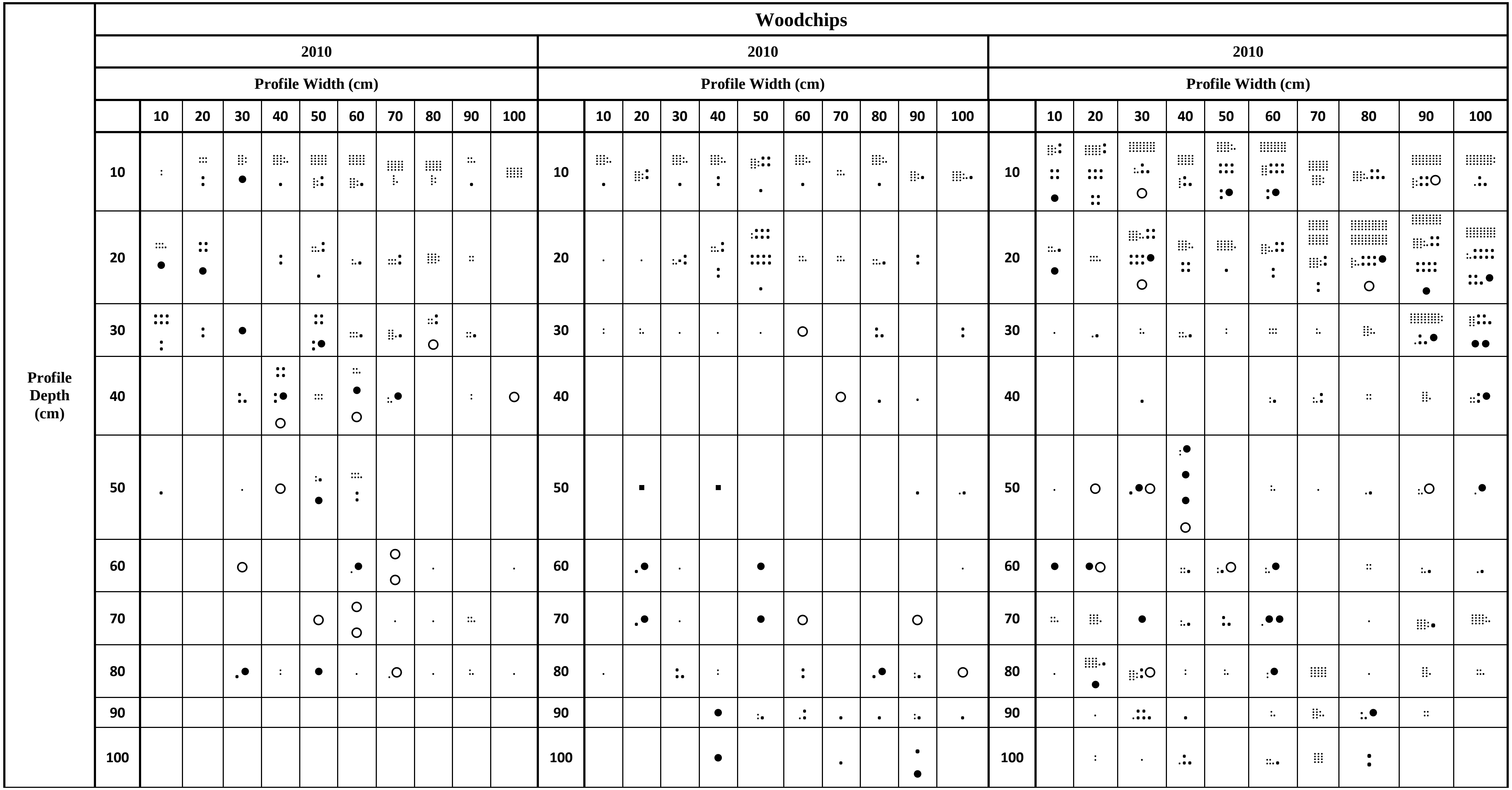

Fig. 21 Total root distribution of the woodchips treatment at 10 cm intervals down the profile of one replicate per treatment in the lighter soil site in the beginning of May 2010, 2011 and 2012, characterized according root diameter* * ⁝ = < 2 mm; **:** = 2-5 mm; • = 5-10 mm; ○ = > 10 mm

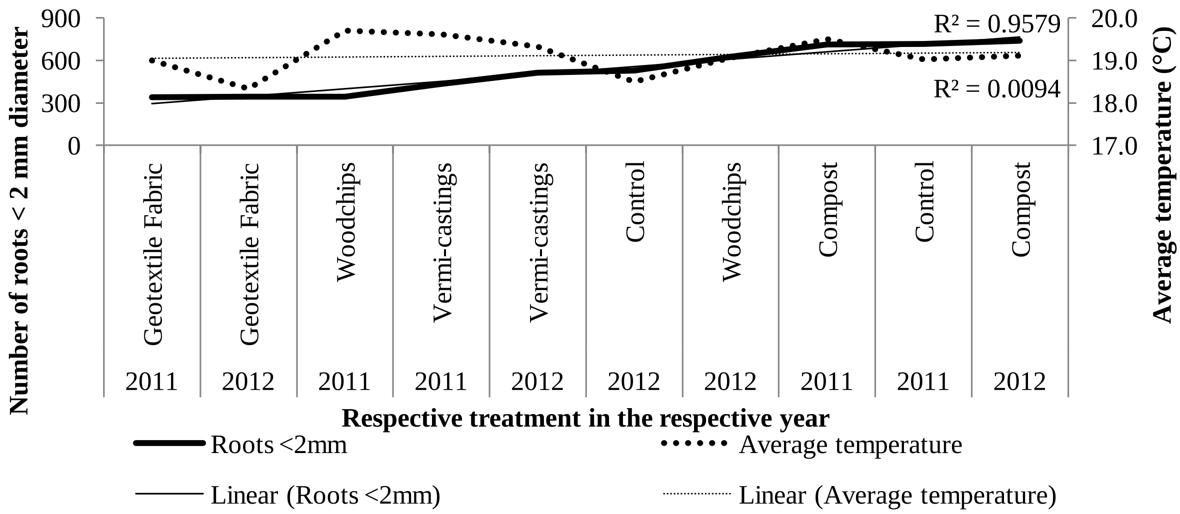

Fig. 22 Linear relationship between the number of roots < 2 mm diameter and the average temperature of the respective treatment in the respective year at the heavier soil site

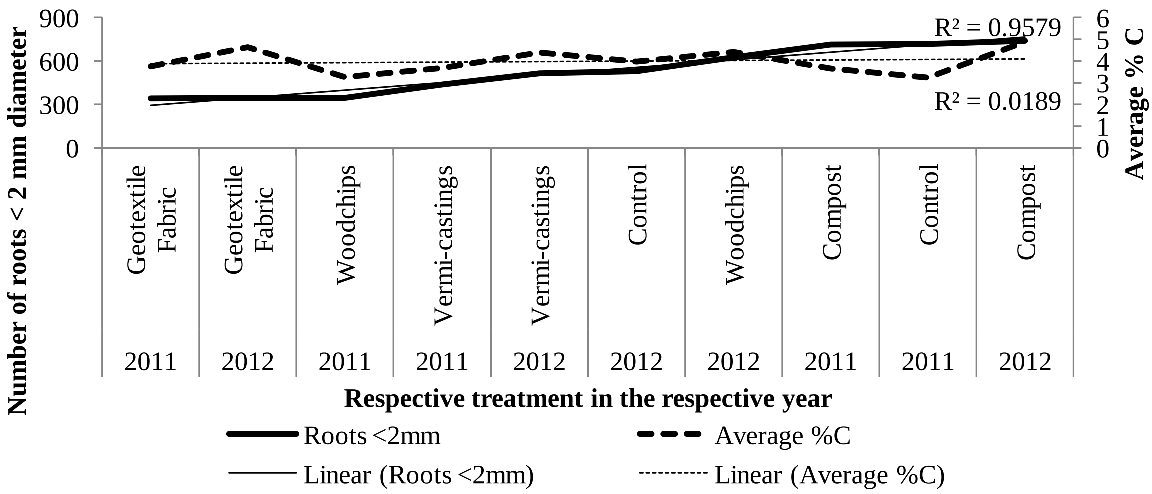

Fig. 23 Linear relationship between the number of roots < 2 mm diameter and the average % C of the respective treatment in the respective year at the heavier soil site

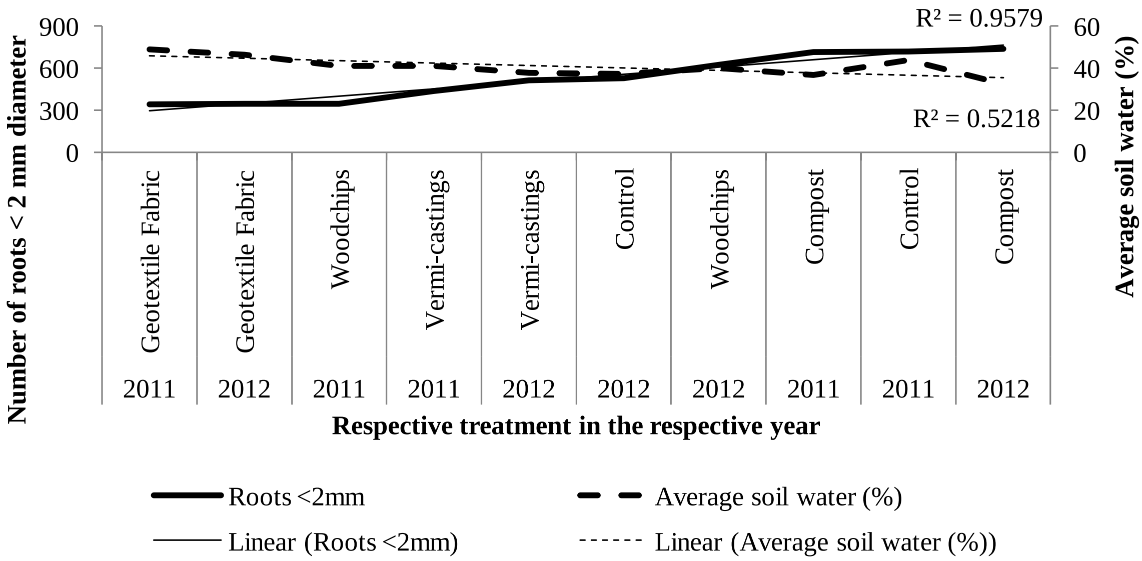

Fig. 24 Linear relationship between the number of roots < 2 mm diameter and the average soil water of the respective treatment in the respective year at the heavier soil site

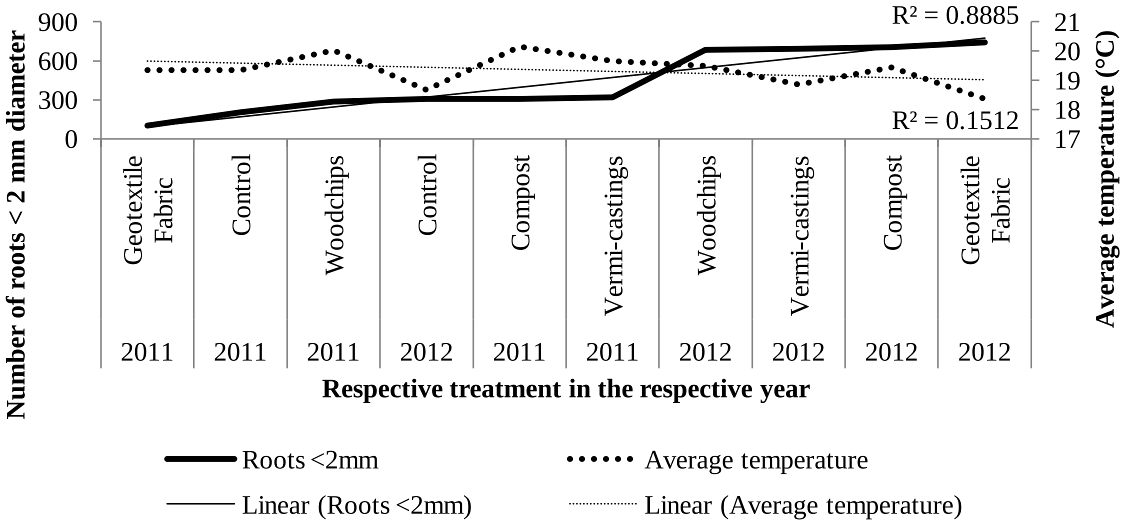

Fig. 25 Linear relationship between the number of roots < 2 mm diameter and the average temperature of the respective treatment in the respective year at the lighter soil site

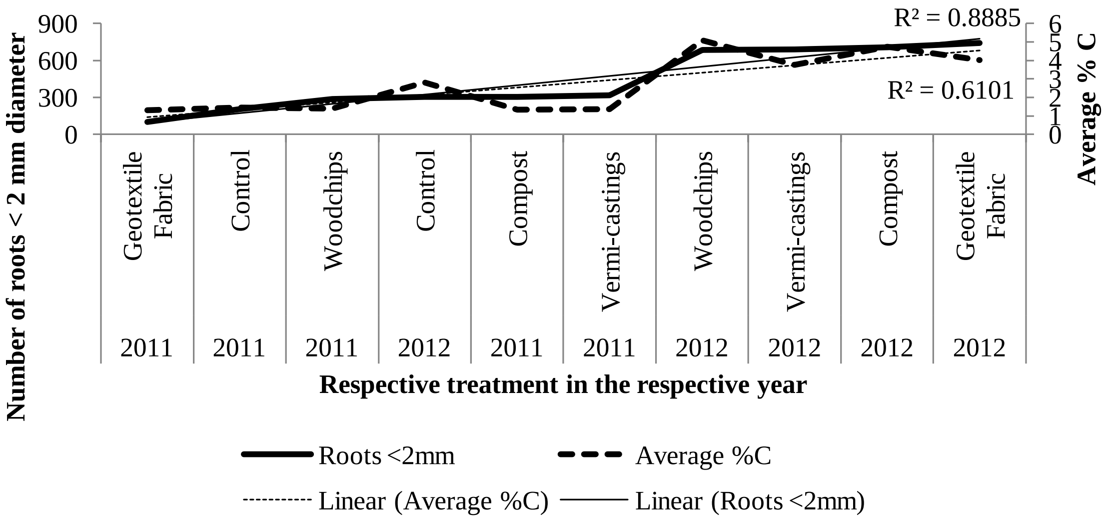

Fig. 26 Linear relationship between the number of roots < 2 mm diameter and the average % C of the respective treatment in the respective year at the lighter soil site

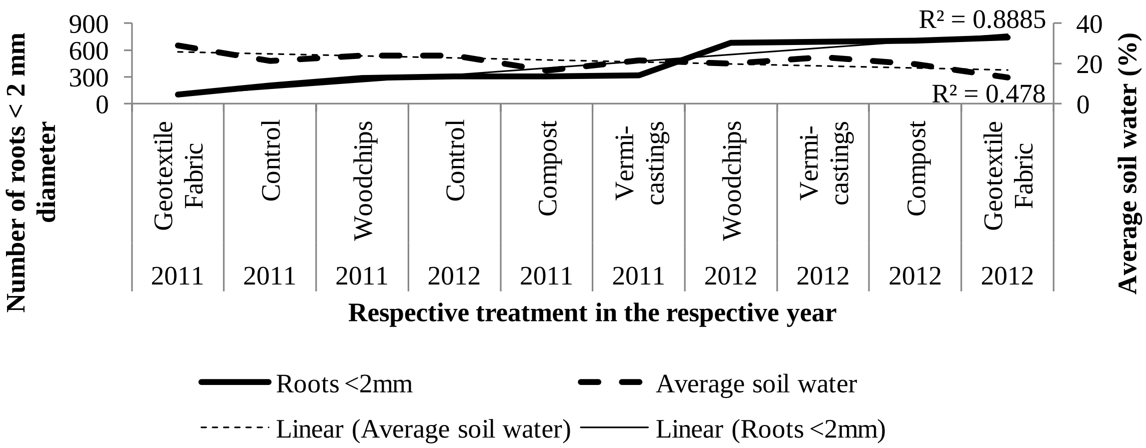

Fig. 27 Linear relationship between the number of roots < 2 mm diameter and the average soil water of the respective treatment in the respective year at the lighter soil site

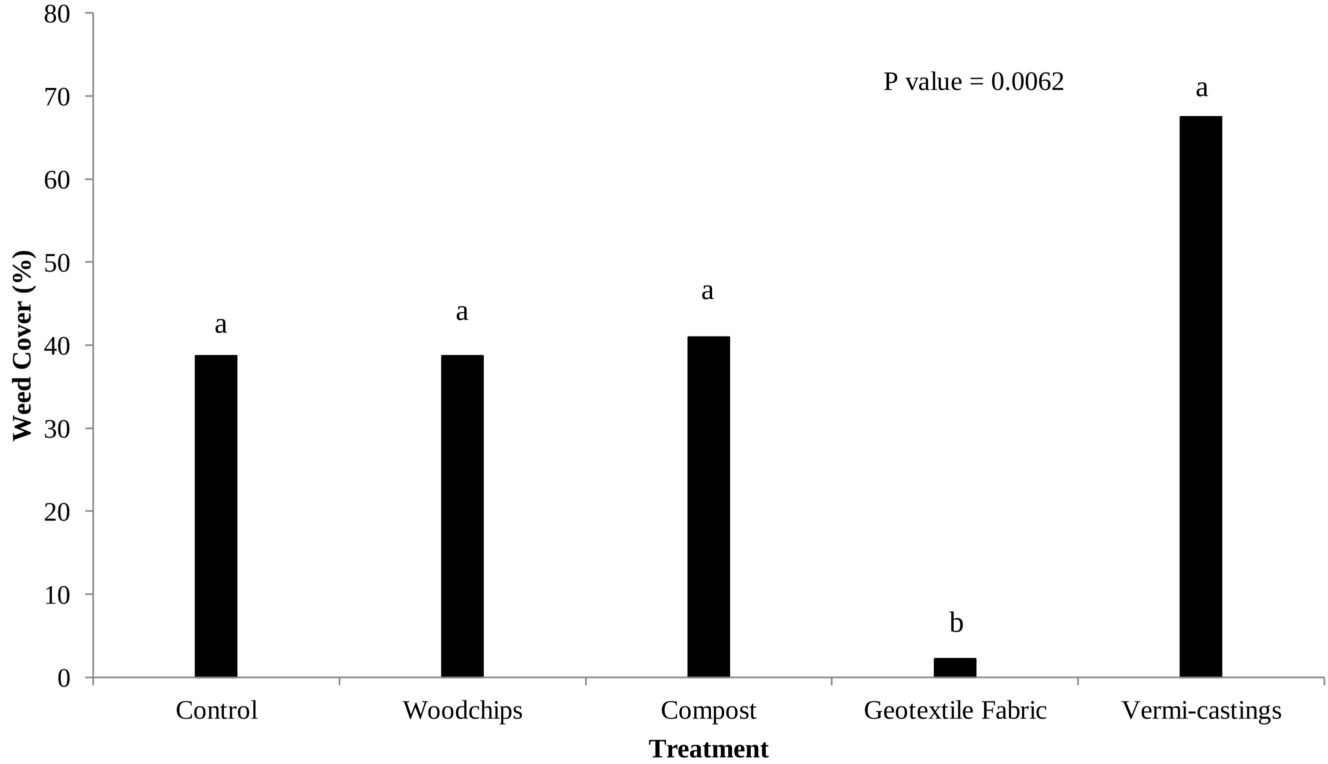

Fig. 28 Percentage summer weed cover in November 2011 in the heavier soil site
* Means with different small letters differed significantly at P<0.05. Means with "ns" were not significantly different.

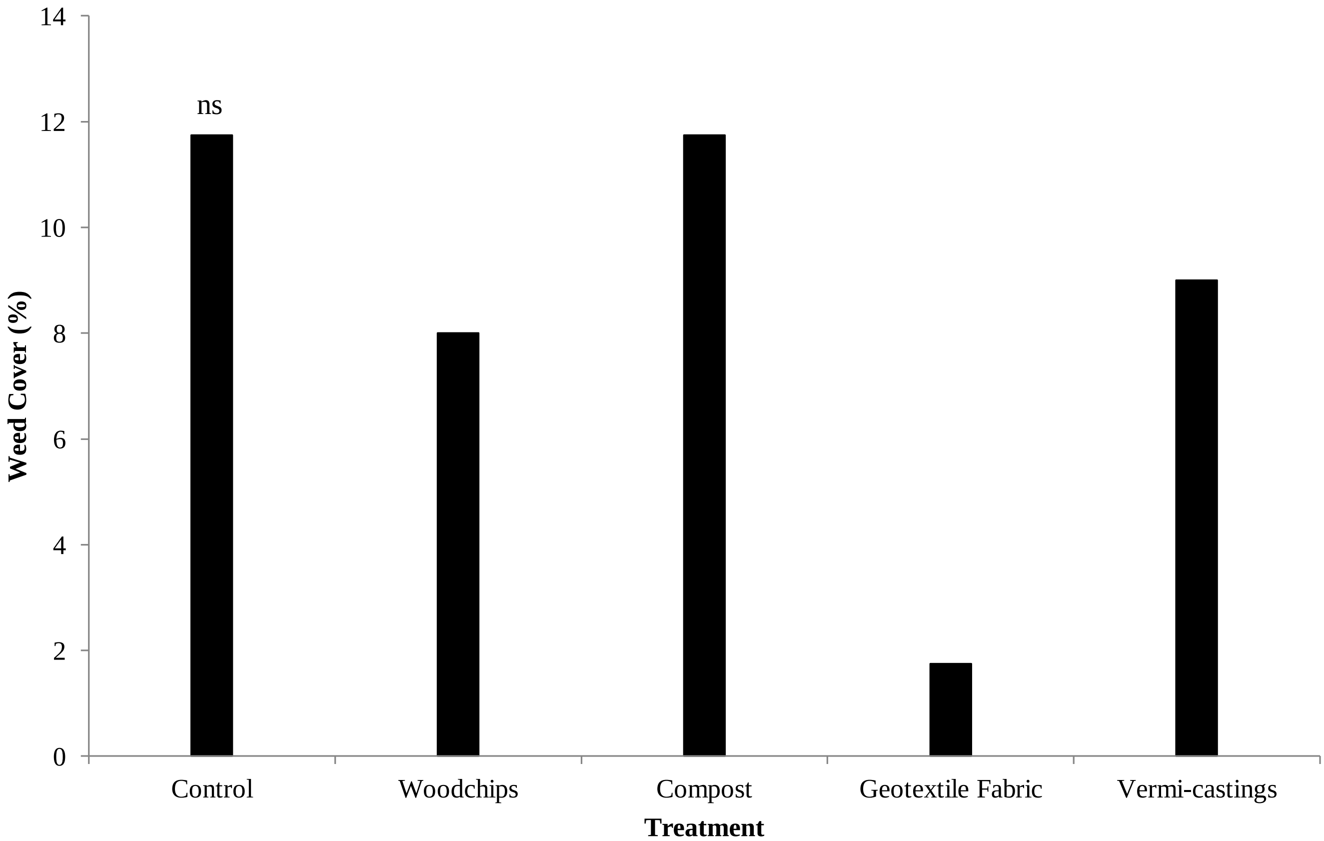

Fig. 29 Percentage summer weed cover in November 2011 in the heavier soil site
* Means with different small letters differed significantly at P<0.05. Means with "ns" were not significantly different.

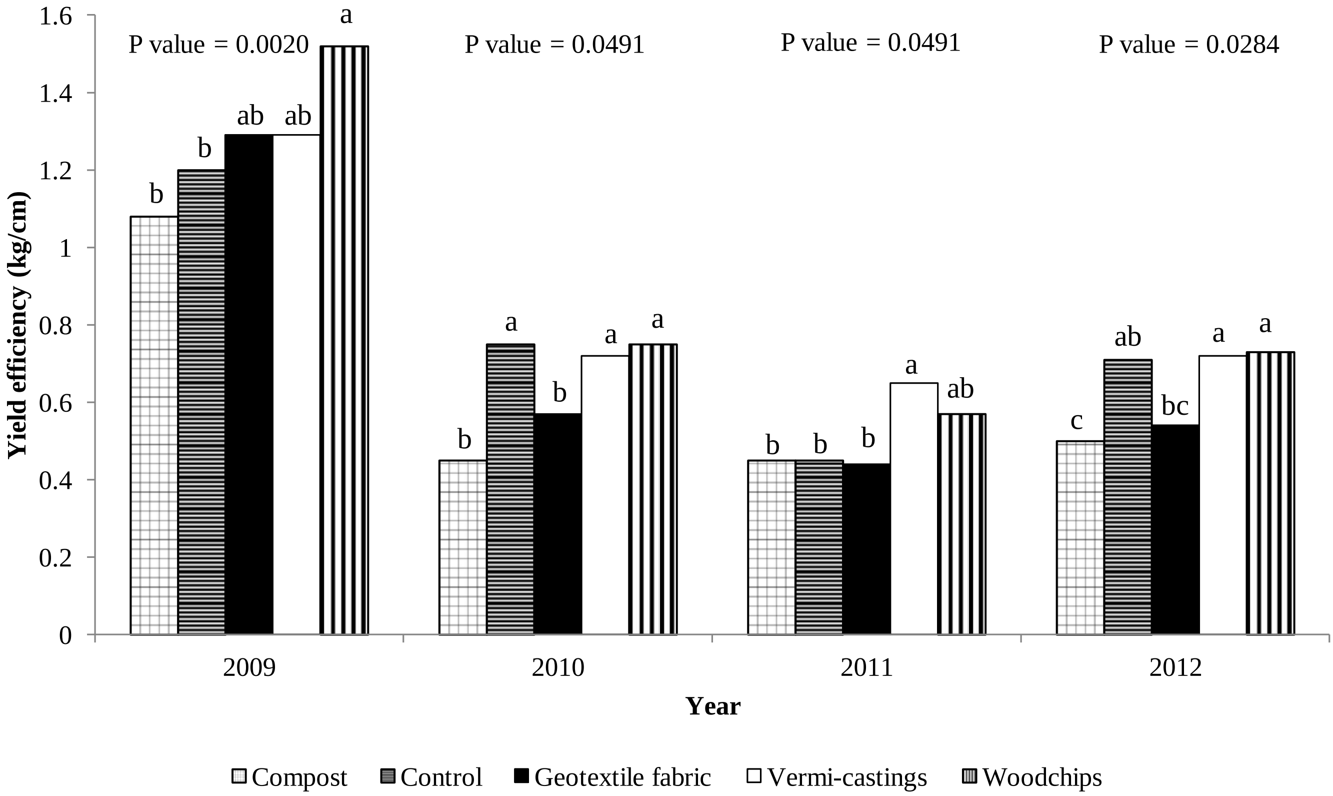

Fig. 30 Yield efficiency over the four years of the trial commencement (2009 – 2012) in the heavier soil site, analysed separately within each year

* Means with different small letters differed significantly at P<0.05. Means with “ns” were not significantly different.

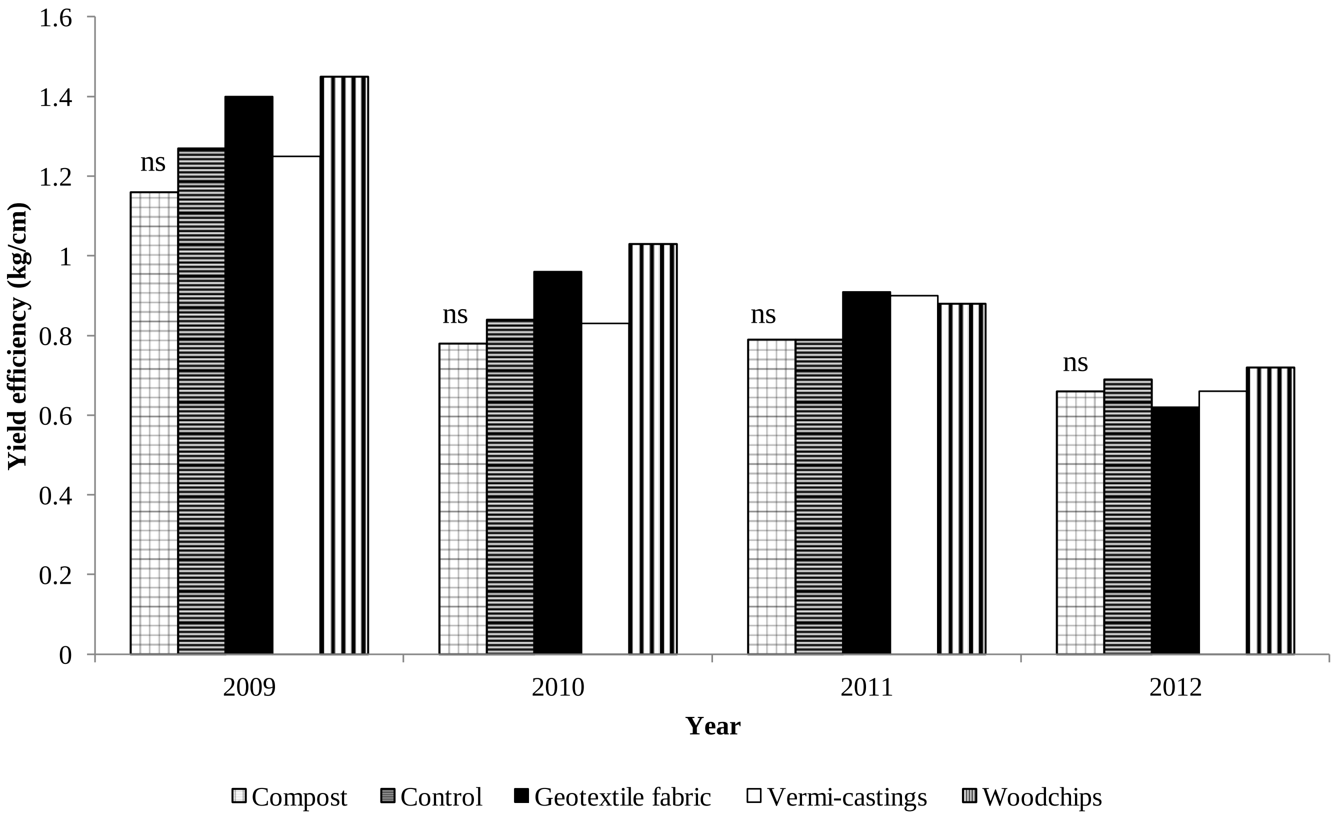

Fig. 31 Yield efficiency over the four years of the trial commencement (2009 – 2012) in the lighter soil site, analysed separately within each year

* Means with different small letters differed significantly at P<0.05. Means with “ns” were not significantly different.

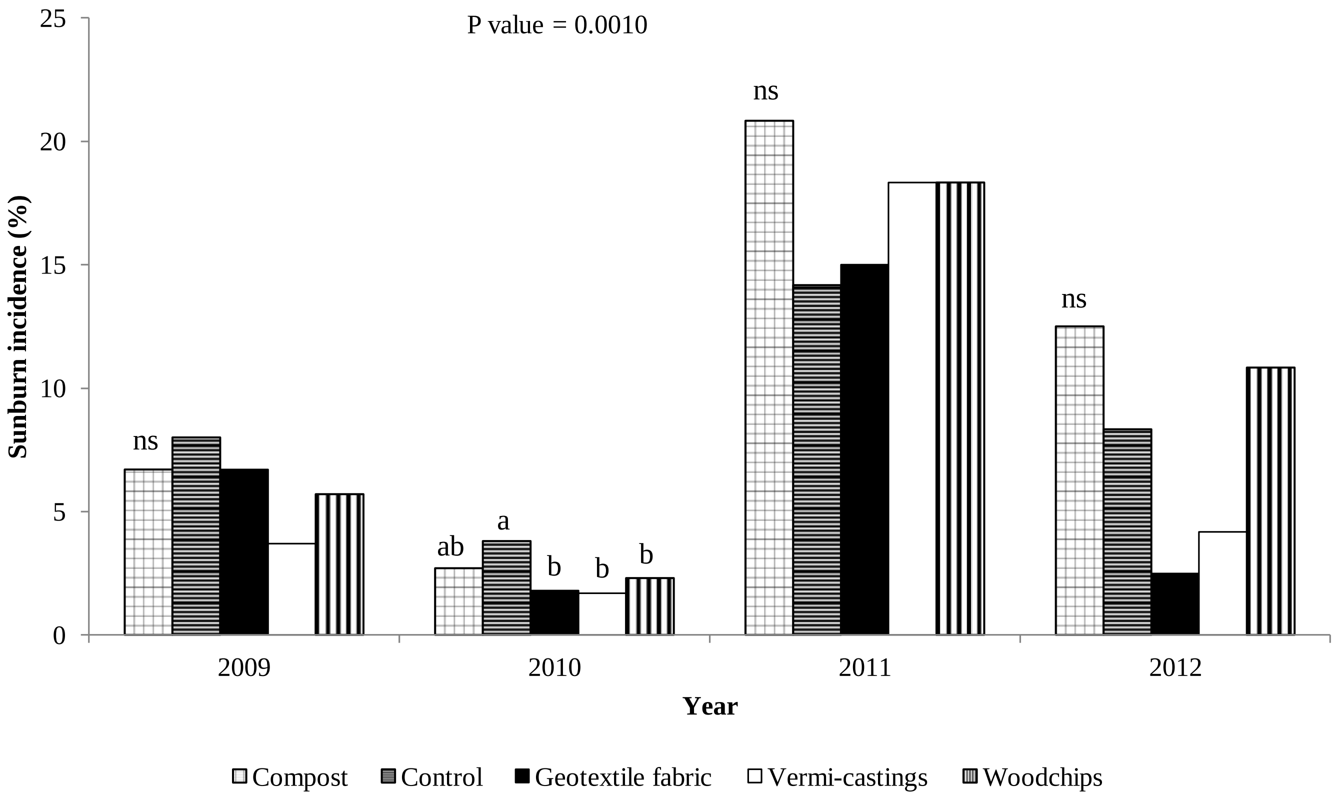

Fig. 32 Sunburn incidence at harvest over the four years of the trial commencement (2009 – 2012) in the heavier soil site, analysed separately within each year

* Means with different small letters differed significantly at P<0.05. Means with "ns" were not significantly different.

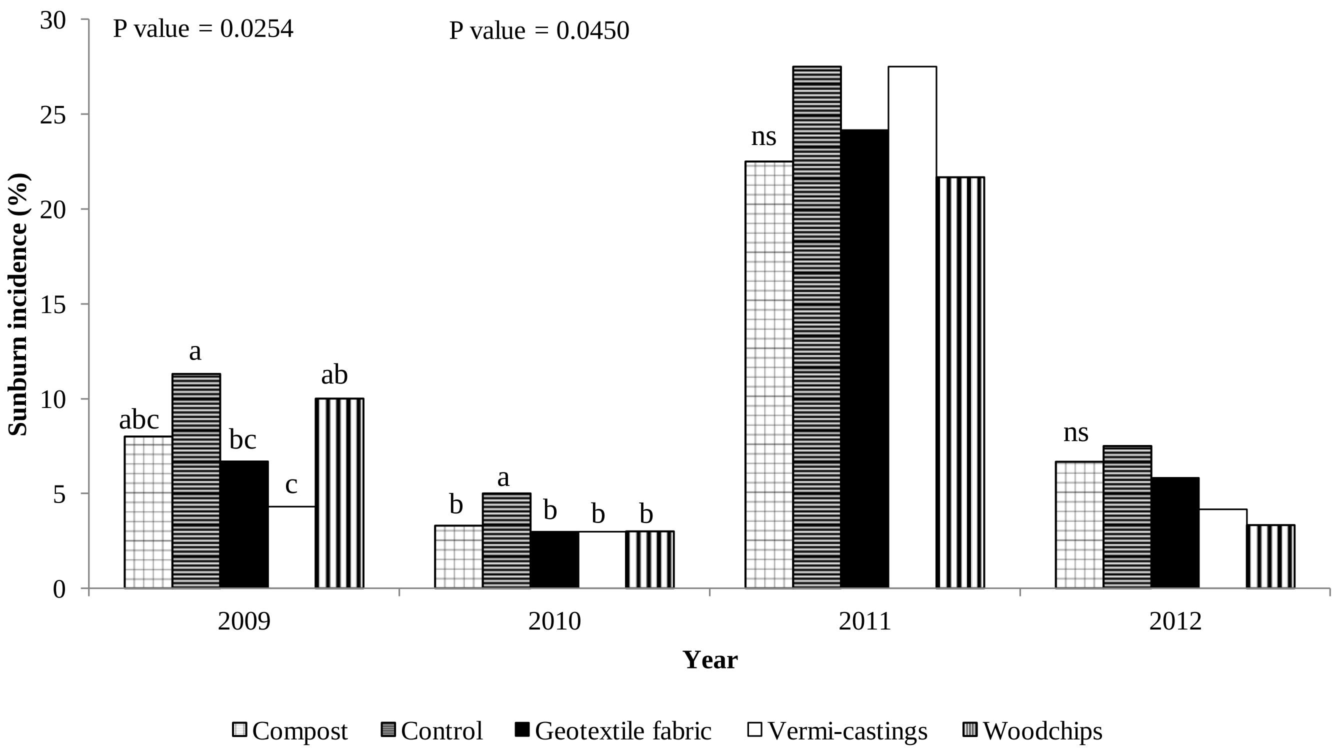

Fig. 33 Sunburn incidence at harvest over the four years of the trial commencement (2009 – 2012) in the lighter soil site, analysed separately within each year

* Means with different small letters differed significantly at P<0.05. Means with "ns" were not significantly different.

Table 2 Fruit nitrogen, phosphorous and potassium at harvest for 2009 and 2012 of the heavier soil site (adapted from Kotze, 2012; v.d. Merwe, in press)

	2009			2012		
Treatment	**N mg/100g**	**P mg/100g**	**K mg/100g**	**N mg/100g**	**P mg/100g**	**K mg/100g**
Compost	35.83[ns]	6.11[ns]	115.83[ns]	43.00[ns]	10.81[ns]	140.50[ns]
Control	37.00	8.07	130.33	39.83	7.81	114.67
Geotextile Fabric	32.83	6.32	119.50	37.50	8.95	113.00
Vermi-castings	35.50	8.12	132.67	43.50	9.41	128.17
Woodchips	31.83	6.01	125.67	40.17	8.19	115.33
P value	0.2062	0.0861	0.3953	0.3749	0.2791	0.1467
LSD	5.0208	2.0470	20.2110	6.8777	2.9524	25.179

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

Table 3 Fruit nitrogen, phosphorous and potassium at harvest for 2009 and 2012 of the lighter soil site (adapted from Kotze, 2012; v.d. Merwe, in press)

	2009			2012		
Treatment	**N mg/100g**	**P mg/100g**	**K mg/100g**	**N mg/100g**	**P mg/100g**	**K mg/100g**
Control	35.33[ns]	5.55[ns]	121.67[ns]	43.33[ns]	6.16[b]	107.00[ns]
Compost	37.83	5.50	130.50	49.00	9.13[b]	134.50
Geotextile Fabric	35.67	5.45	121.33	54.83	9.11[b]	120.67
Woodchips	37.83	6.64	124.00	52.17	9.55[ab]	119.50
Vermi-castings	36.50	5.19	119.67	53.33	12.48[a]	146.67
P value	0.8133	0.2902	0.3912	0.4446	0.0134	0.0660
LSD	5.5508	1.4394	16.656	13.645	3.3948	27.820

* Means with different small letters differed significantly at P<0.05. Means with different cap letters differed significantly at P<0.10. Means with "ns" were not significantly different.

General Conclusion

This trial aimed to investigate the effects of different mulches on the root environment, encompassing physical, chemical and biological factors of the soil, on two different soil types in the form of a field trial on 'Cripps' Pink' apples. Three organic mulches were tested: compost, vermi-castings and woodchips, as well as an inorganic mulch, geotextile fabric, and were compared against clean cultivation.

The different mulches were assessed against each other as well as an un-mulched treatment in both sites, according to their ability to change and improve the physical, chemical and biological factors of the soil important for root growth, and ultimately their effects on fruit yield and quality.

It is clear from the combined results that the effects of mulching are dependent on the type of soil that is being covered and the outcomes that are intended on being achieved.

The compost treatment was successful in improving physical characteristics of the soil in the heavier soil, such as a low resistances and intermediate bulk densities (lower than the control and geotextile fabric treatments). It did not however, feature too prominently in the lighter soil in this regard. The compost treatment was also efficient in keeping the temperatures fairly constant during the season in both sites. However, other organic mulch treatments were more successful in keeping the soil temperatures higher during the season. In the heavier soil, higher temperatures were achieved by this treatment during warmer times in the season; this was accompanied by lower moisture levels. In contrast, the compost treatment showed lower temperatures and higher moisture levels in the lighter soil. It can therefore be concluded that the performance of the compost treatment is dependent on the type of soil, and the mulch can have a direct effect, secondary effect, or both on temperature and moisture, which in turn has a secondary effect on one another. In addition, the compost treatment realised consistently higher mychorrizael colonization during three out of the four seasons in both sites. However, the colonisation was not always significantly higher than the other treatments. The compost material was therefore successful in ameliorating the heavier loam with regard to physical properties, and both heavier and lighter loams with regard to biological properties, and as result achieved the highest root count in 2012 for the heavier soil site.

The vermi-castings treatment was very effective in improving physical characteristics of the heavier soil as it achieved the lowest resistance and intermediate bulk densities. It also resulted in a significant increase in silt concentration. Due to the improved physical characteristic of the soil, moisture and temperature levels were stabilized and remained intermediate compared to the other treatments in both sites. The vermi-castings treatment was most effective in preventing temperature fluctuations and moisture contents in the lighter soil and occurred at intermediate to high levels. The primary attributes to mulching (temperature stabilization and water conservation) were therefore achieved by the vermi-castings treatment in both sites. In addition, the vermi-castings mulch was superior in increasing nutrient levels in the soil of the heavier soil site. In contrast to the heavier soil, no treatment could ameliorate the nutrient status of the lighter soil, with the exception of the increased percentage C as a result of the compost and vermi-castings treatments. The significantly higher levels of nutrients (macro and micro) (P, N, K, Mg, Zn, Mn, B) and exchangeable cations (Na^+, K^+, Ca^+, Mg^+) achieved by the vermi-castings treatment in the heavier soil were largely due to the notably higher nutrients in the mulching material, prior to application. The other organic mulching materials, followed the trend of the vermi-castings material in achieving high levels of these nutrients. The effect can therefore be direct, in terms of nutrient addition by the increased organic matter, or indirect, in terms of soil environment amelioration by the organic matter, resulting in increased nutrient levels. The lack of nutrient status improvements as a result of mulching in the lighter soil site may be due to the nature of the lighter textured soil, allowing for more leaching of the nutrients. This was supported by the lack of change in physical properties of the soil in the lighter soil site as a result of mulching. It was highly successful in enhancing the root environment in both sites, however did not result in increases in root counts that were achieved by the other organic treatments. In this instance, the tree did not require an extensive root system in order to support a good yield and more energy was therefore allowed for reproductive growth as opposed to vegetative growth.

The woodchips treatment resulted in mixed reviews with regards to physical changes to the soil. Unfavourably high resistances in the heavier soil as a result, but it achieved a low bulk density. Nevertheless, the woodchips treatment was successful in stabilizing temperature fluctuations and warming the soil throughout the season. In the heavier soil it resulted in intermediate moisture levels, however in the lighter soil, low moisture levels were achieved.

This confirms the statement that mulches are suited for different soil types and different functions. The woodchips achieved superior root counts in both sites, regardless of the negative results in some of the soil factors.

Physical, chemical and biological attributes to the organic mulching materials, mentioned above, are largely associated with the addition of organic matter to the soil, and the increase thereof, on and near the soil surface. The increase in C by the organic mulch treatments in the lighter soil provides evidence that organic mulches increased the organic matter near the soil surface. Therefore, the organic mulch treatments, and particularly that of the woodchips and compost treatments in the heavier soil, achieved higher fine root counts and better distribution thereof.

The geotextile fabric treatment was not as successful in achieving the extent of improvement on the physical characteristics of the heavier site as the compost treatment did, but realised an intermediate bulk density which was lower than the control treatment. Notable fluctuations in temperatures occurred as a result of the geotextile fabric treatment in the heavier soil, particularly during times of hot days and cool nights, which are important for 'Cripps' Pink' fruit quality development. Although temperatures in this site fluctuated considerably, moisture levels were higher in the upper layers of the soil, which is an unusual accompaniment for fluctuating temperatures. It can therefore be concluded that, due to the lack of physical improvement in the soil as a result of the mulch, water was trapped in the upper layers of the soil in the heavier soil as a result of physical breakdown causing compaction to occur, which is known to happen under plastic mulches. In the lighter soil site temperatures did not fluctuate as much, however moisture levels were lower which suggests that more drainage was able to occur and physical characteristics of the soil did not deteriorate as they did in the heavier soil site. As result, the inorganic treatment ultimately performed the best with regard to root counts and distribution in the lighter soils. Covering the soil with dark fabric reduced the germination and growth of summer weeds considerably, as seen with the geotextile fabric treatment in both the heavier and lighter soils.

Although the root environment was changed and root volumes were altered and improved by mulching, fruit quality was not changed. It is possible that fruit quality may benefit from these changes in years to come.